SOME FEATURES OF THE GULF STREAM OFF CHESAPEAKE BAY IN THE SPRING OF 1963[1]

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ABSTRACT

Oceanographic measurements in May and June 1963, showed that water mixing was intense though intermittent at the western boundary of the Gulf Stream. Warm, saline water became separated from the Stream and mixed with the slope water as a result of divergence near the surface and upwelling. Data from repeated sections along three transects of the Gulf Stream are analyzed and presented in 22 cross-sectional plots. These plots show that a zone of intense mixing appeared intermittently at the western side of the Gulf Stream in an apparently fluctuating manner. Separation of this mixing zone from the Gulf Stream resulted from local ascent of cool water from the subsurface levels where there was a zone of steeply sloping isotherms. The results suggest that part of the mixed, dense water sank to about 200 m. below the depth at which it was produced and returned to the Gulf Stream.

Data for this report were obtained during Cruise 1 of the Bureau of Commercial Fisheries research ship *Geronimo* (May 8 to June 7, 1963). Although the primary purpose of the cruise was to test the ship and its gear, extensive physical and biological oceanographic observations were also made. The principal physical investigation was a study of the properties of the Gulf Stream along three transects described as follows (fig. 1):

Transect I—16 sections across the left (inshore or western) boundary of the Gulf Stream—12 with bathythermograph observations only, and 4 with oceanographic stations (Nansen bottle casts) and BT's.

Transect II—four sections across the left boundary (all with oceanographic stations and BT's).

Transect III—three sections across the left boundary (all with oceanographic stations and BT's).

Most of the data used in this report were gathered by repeated occupation of these transects. For each transect, one section was extended southeastward into the Sargasso Sea. The right (offshore or eastern) boundary of the Gulf Stream was crossed six times.

Bathythermograph observations were taken every 5 nautical miles (9.3 km.), except that on a supplementary run from transect II to transect I along the left boundary, BT's were taken every 10 miles (18.5 km.). Observations at the oceanographic stations were limited to the upper 600 m. The last one or two digits in the numbers of the hydrographic station locations used in this report (fig. 1) indicate their chronology.

Continuous records of surface temperature were made with a Foxboro[3] thermograph and were checked by measurements with two thermistors and one bucket thermometer at the location of each BT observation. Portions of the Foxboro temperature records are reproduced (figs. 2 and 3 to 25). The lower trace on the temperature record is used when the upper trace exceeds the scale and is usually set 10° C. below the upper. The lower trace was not well controlled during this study, and the difference at times exceeds 10° C.

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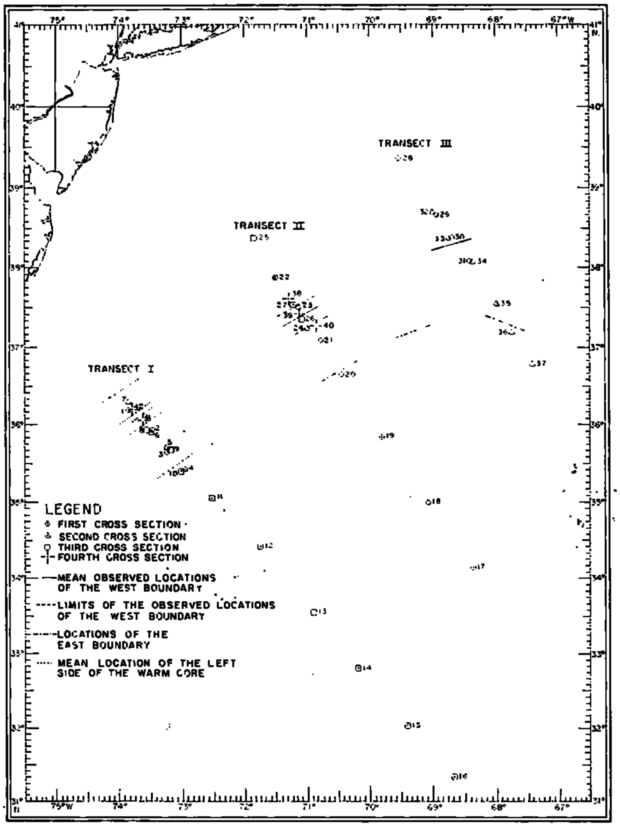

FIGURE 1.—Locations of transects and (oceanographic) stations of R.V. *Geronimo* Cruise 1.

Continuous representation of the Gulf Stream structure along its axis is not possible because the observations were concentrated on transect lines about 140 miles (259.4 km.) apart. The detailed observations along each line do reveal a number of common properties among the

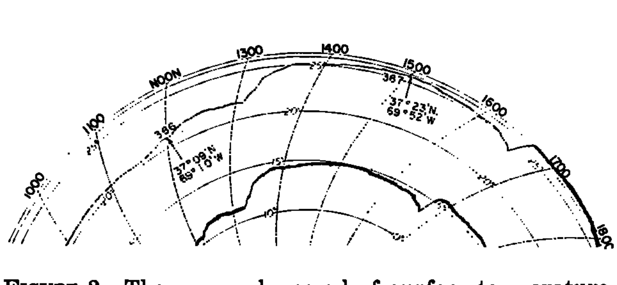

FIGURE 2.—Thermograph record of surface temperature change across the right boundary of the Gulf Stream between transects II and III. Temperatures greater than 25° C. are read from the lower of the two traces by adding 10° C. to the individual values. Bathythermogram numbers and locations are indicated along the temperature trace.

transects. Most sections extend across only the left boundary of the Gulf Stream; therefore, my main intent is to interpret some variable and transient features of that boundary.

BOUNDARY SYSTEM

In defining the boundary system, I will describe the temperature structure in the area between the slope water and the Sargasso Sea.

SLOPE WATER—INTERMEDIATE WATER BOUNDARY

From the slope water to the Gulf Stream, the surface temperature increased in two steps along most of the sections. In a typical case (fig. 10), the first step was a positive gradient of about 8° C. in less than 1 mile (1.9 km.); this temperature increase was the offshore (eastern) boundary of the slope water. Beyond this first step was a rather wide intermediate area of very irregular surface temperatures. Another steep, positive surface gradient of about 4° to 6° C. was at the left boundary of the Gulf Stream; in most sections this gradient was above or slightly left of the zone of steeply sloping isotherms in the subsurface layers. Iselin (1936) reported similar observations of the slope water and Gulf Stream boundaries.

INTERMEDIATE ZONE

The width of the intermediate zone—between the offshore slope water and the inshore Gulf Stream boundaries—varied greatly. At times it was not observed at all; at other times it was as wide as 60 miles (111.1 km.). For example, the zone is practically nonexistent in figure 5, where surface temperature increased from 12° to 22° C. in about 3 miles (5.6 km.), followed by an increase of only about 2° more in the next 20 miles (37 km.) (the distance to the warm core). A contrasting situation is illustrated in figure 18, in which the intermediate zone is about 50 miles (92.6 km.) wide and the warm core of the Gulf Stream is immediately to the right of the Gulf Stream boundary.

LEFT BOUNDARY OF THE GULF STREAM

The left boundary of the Gulf Stream is defined here as the first strong thermal gradient crossing at the surface from the Gulf Stream toward the slope water. The mean location of

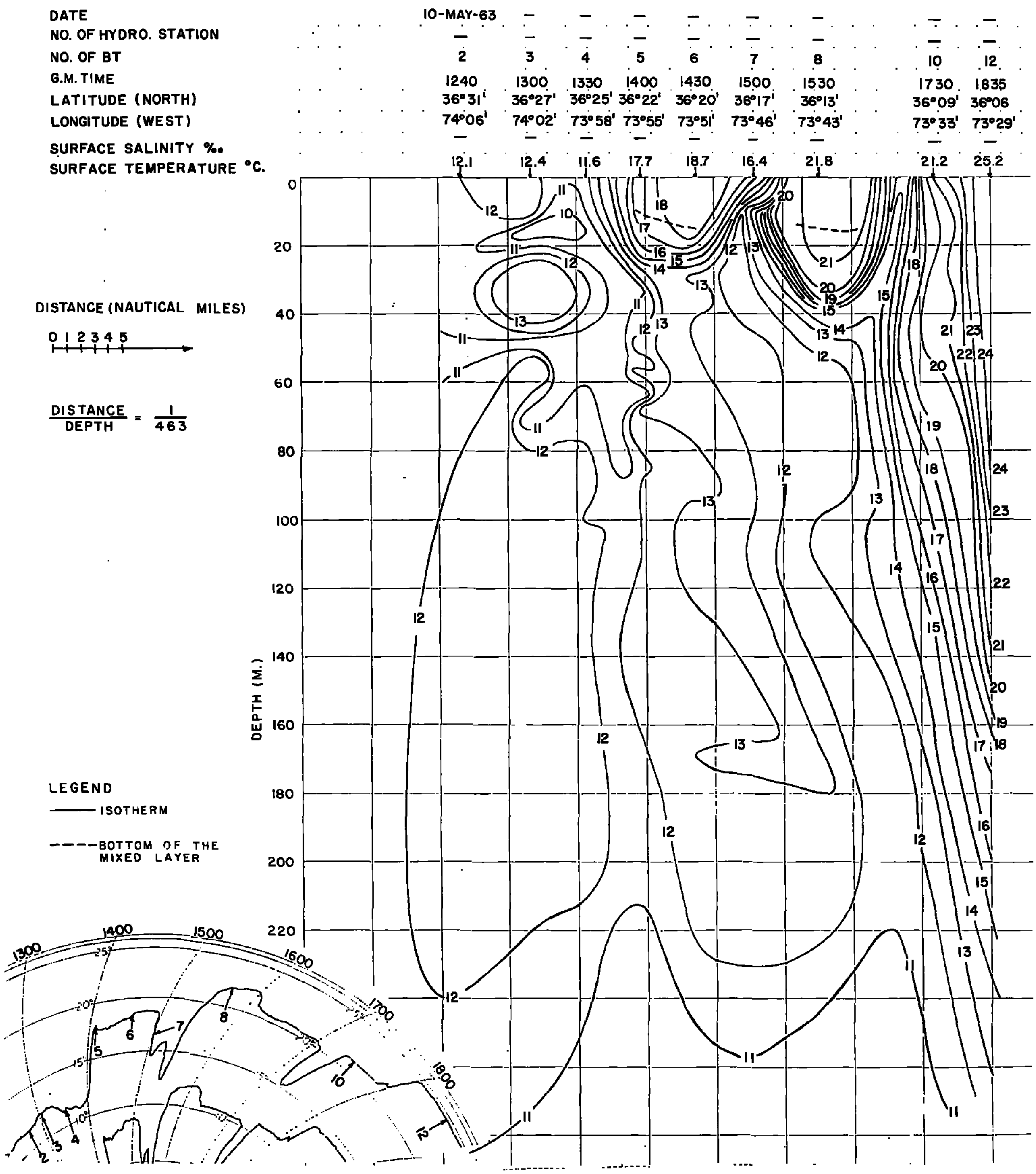

FIGURE 3.—Transect I—Section 1, May 10, 1963. Vertical temperature profile and thermograph record of surface temperatures. Thermograph temperatures greater than 25° C. are read from the lower of the two traces by adding 10° C. to the individual values. Bathythermogram numbers appear along the surface temperature trace to show the time of the casts.

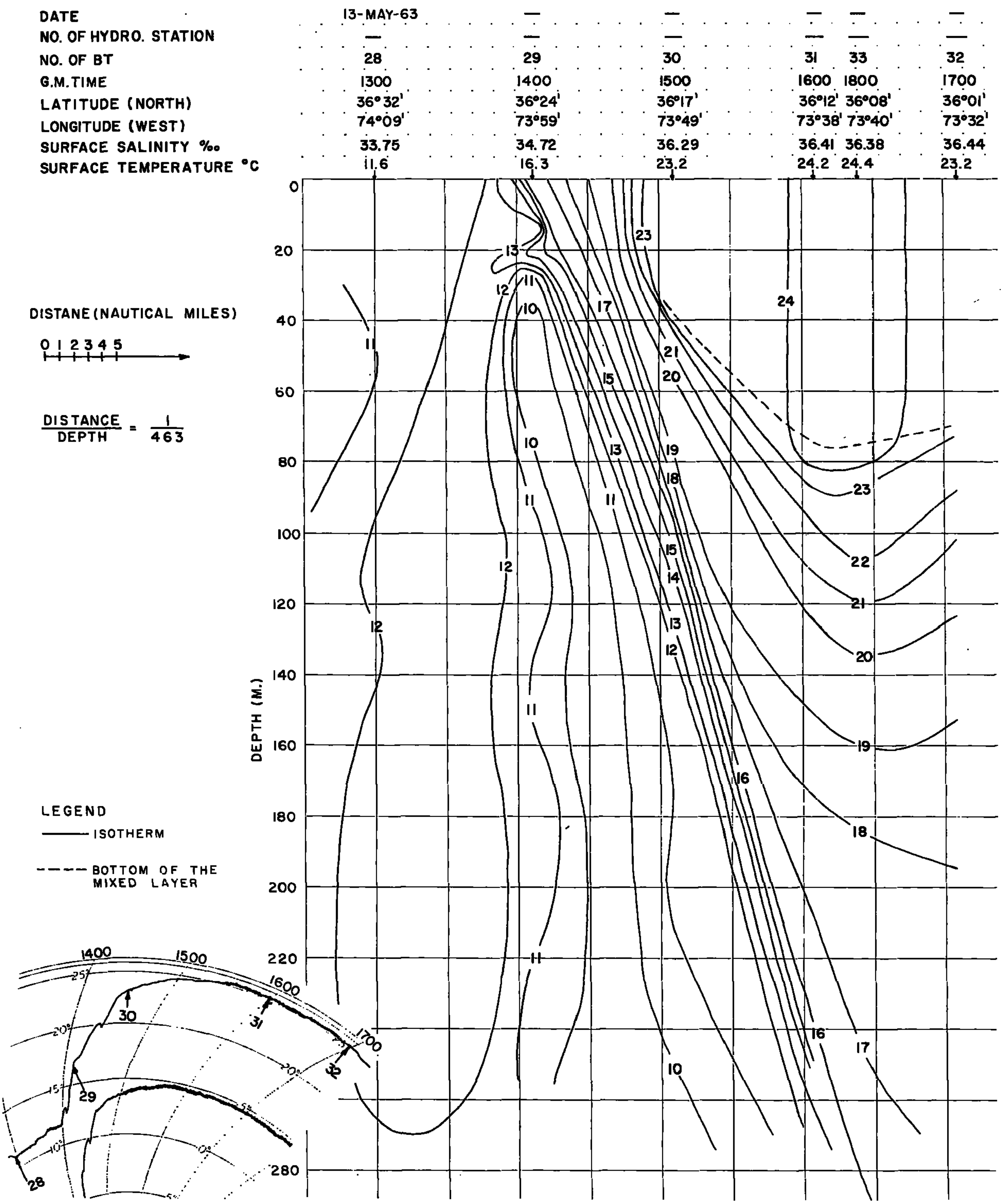

FIGURE 4.—Transect I—Section 2, May 13, 1963. (*See* caption for fig. 3.)

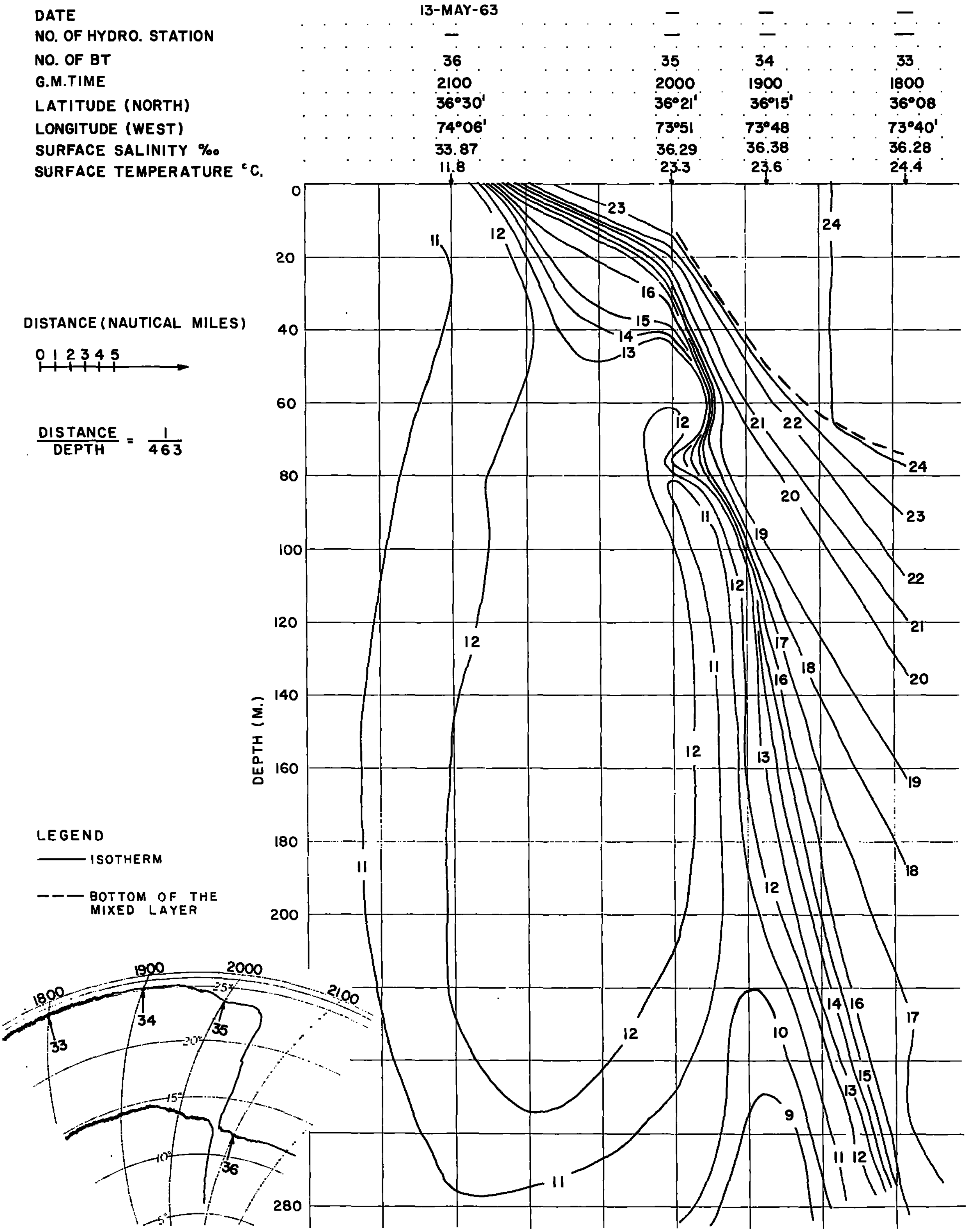

FIGURE 5.—Transect I—Section 3, May 13, 1963. (*See* caption for fig. 3.)

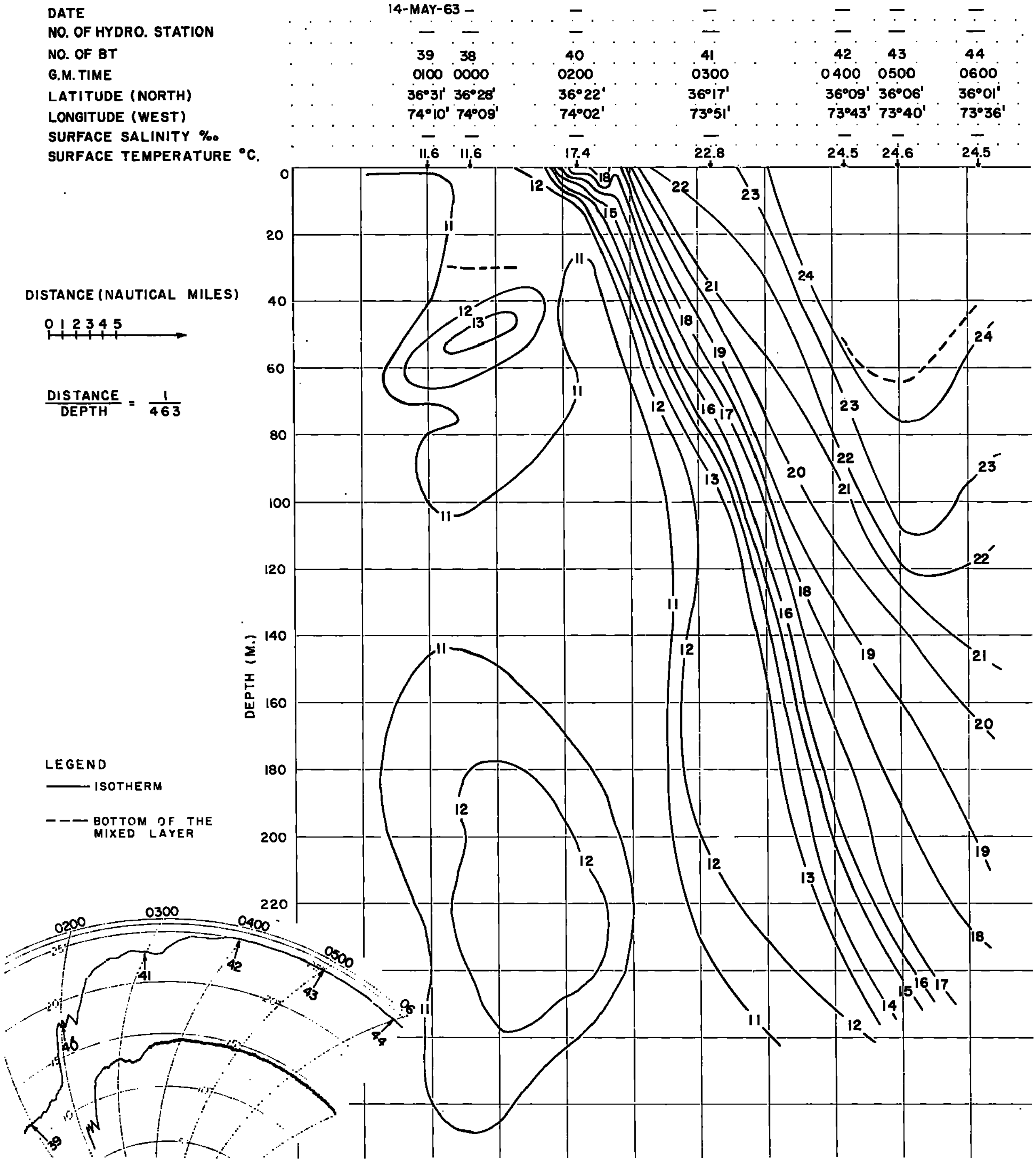

FIGURE 6.—Transect I—Section 4, May 14, 1963. (*See* caption for fig. 3.)

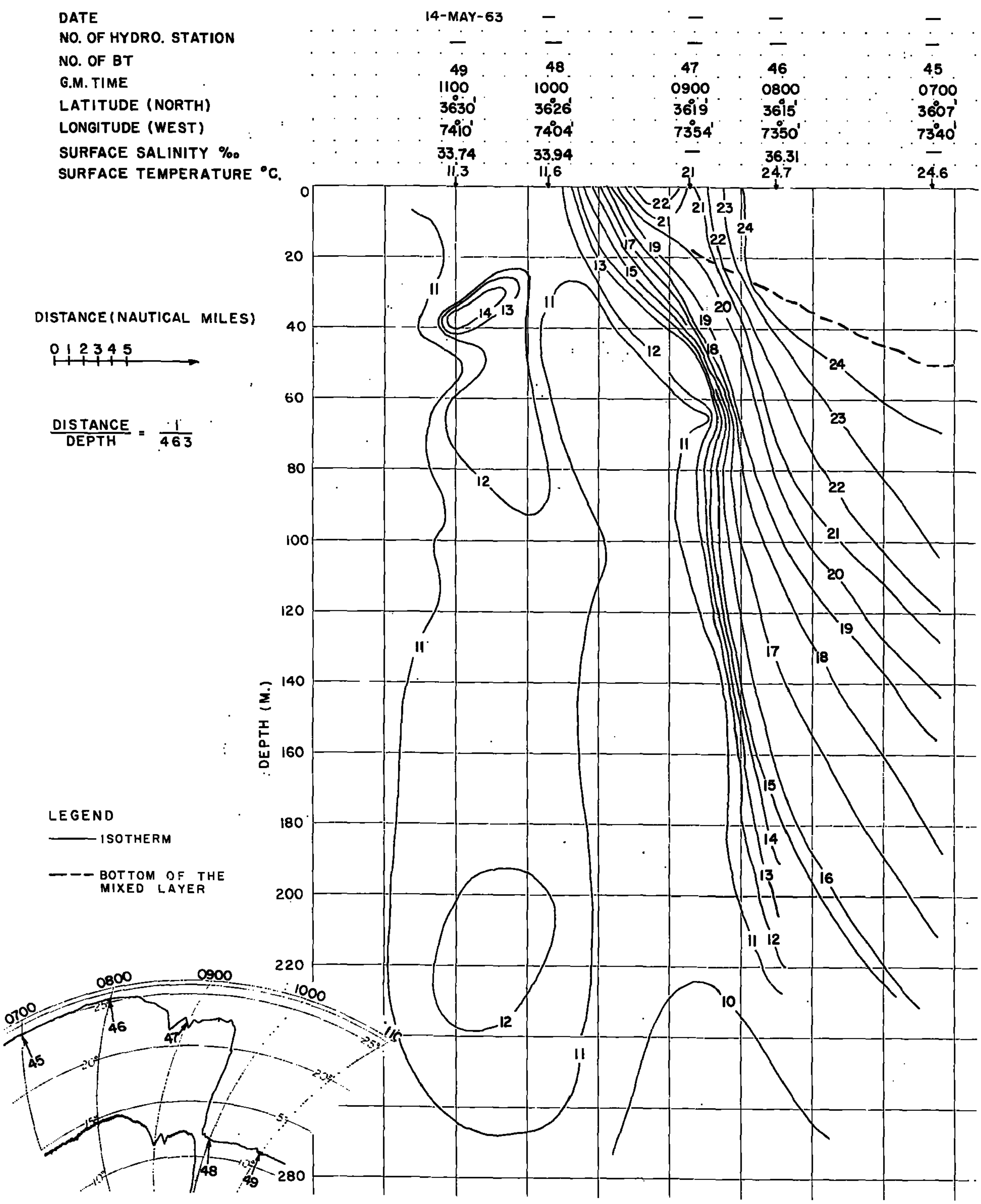

Figure 7.—Transect I—Section 5, May 14, 1963. (*See* caption for fig. 3.)

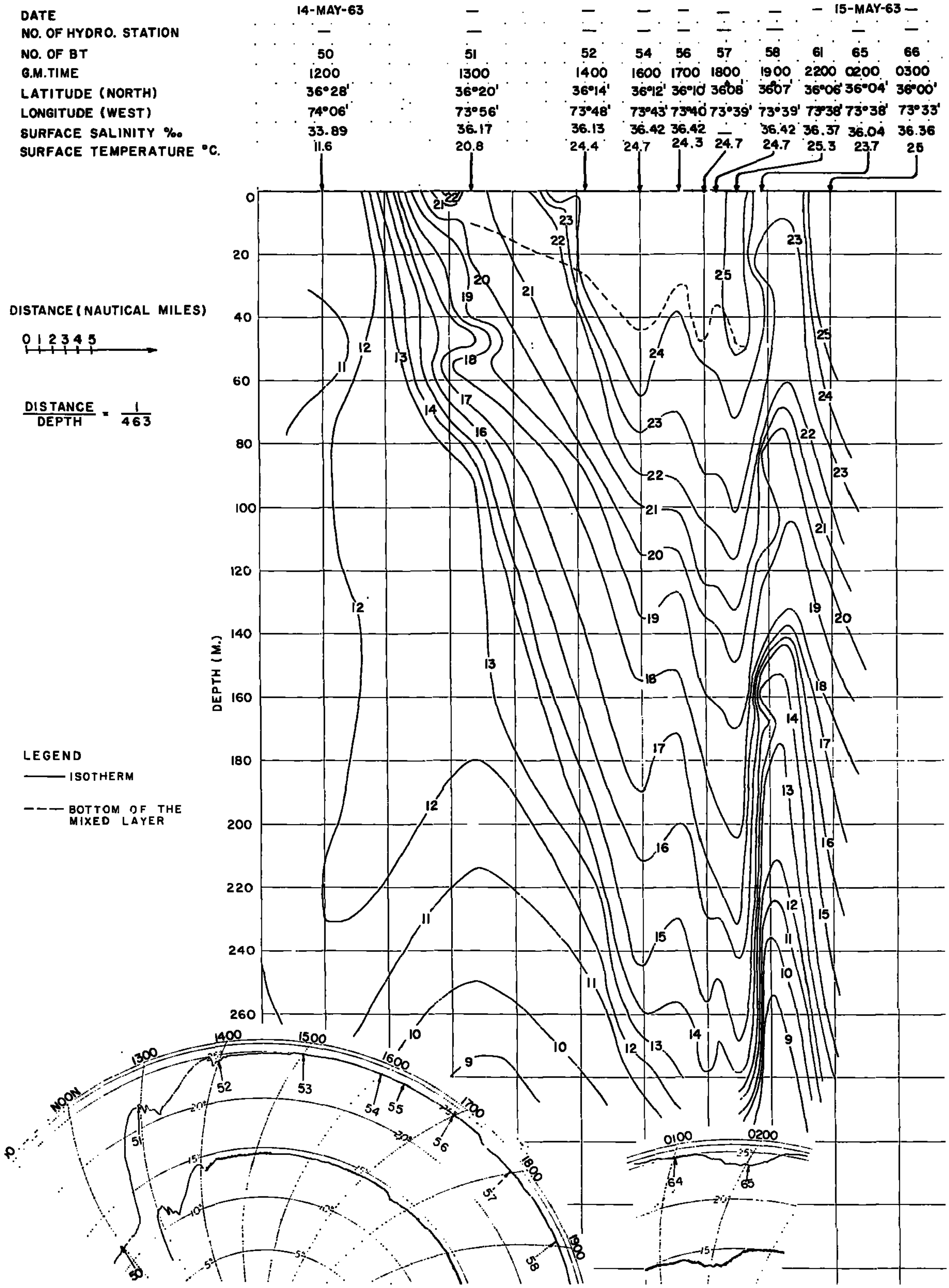

FIGURE 8.—Transect I—Section 6, May 14, 1963. (*See* caption for fig. 3.)

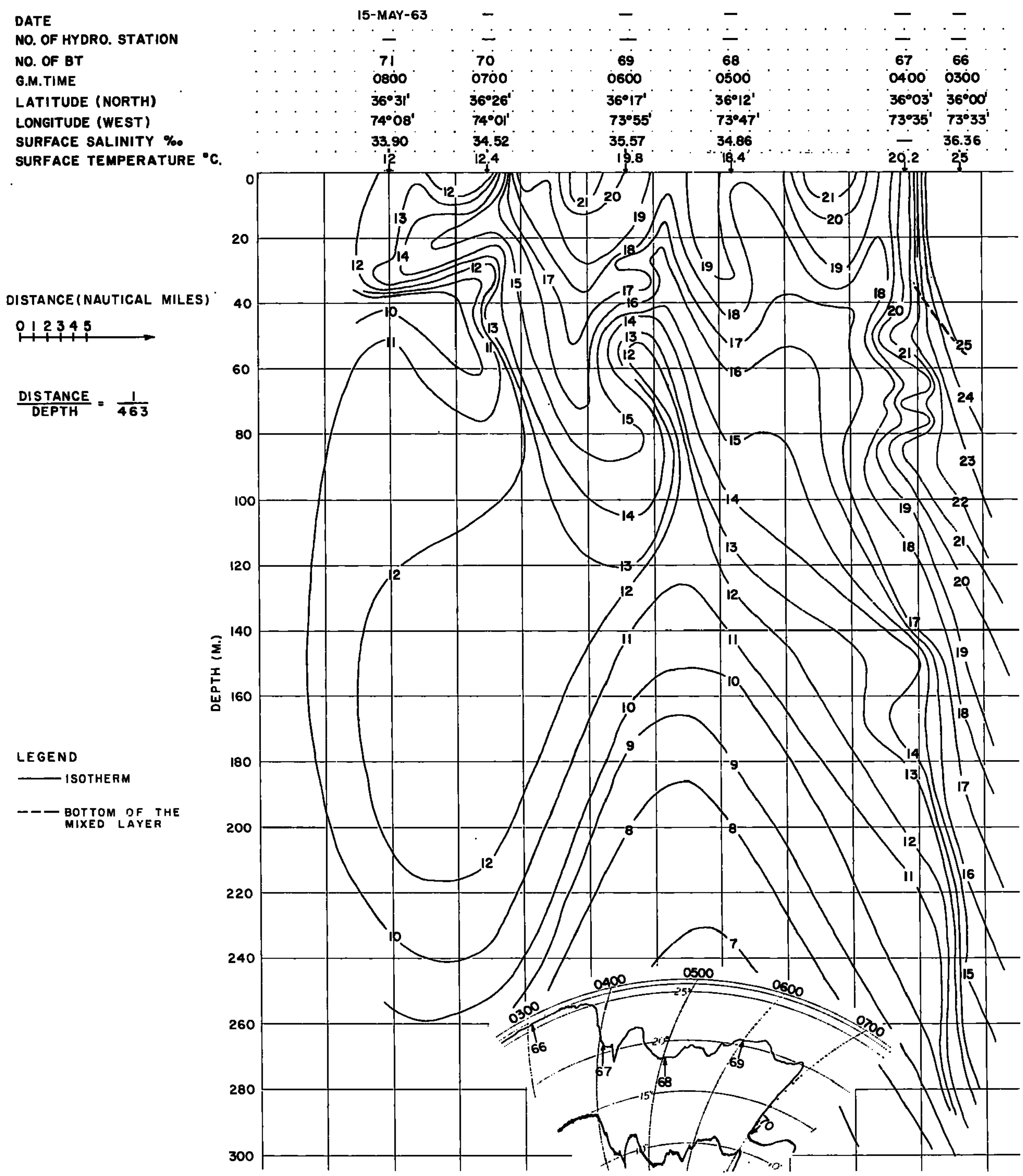

FIGURE 9.—Transect I—Section 7, May 15, 1963. (*See* caption for fig. 3.)

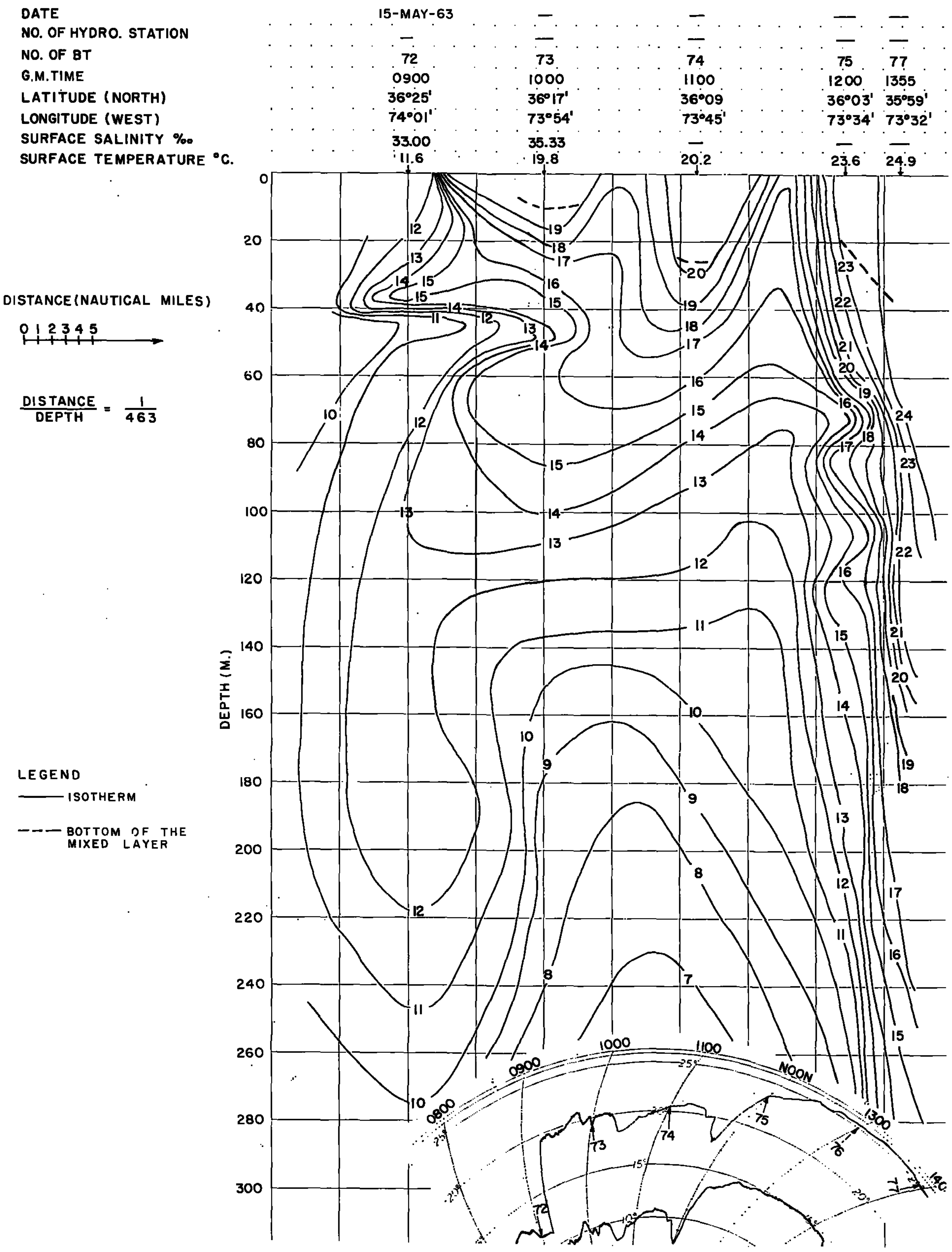

FIGURE 10.—Transect I—Section 8, May 15, 1963. (*See* caption for fig. 3.)

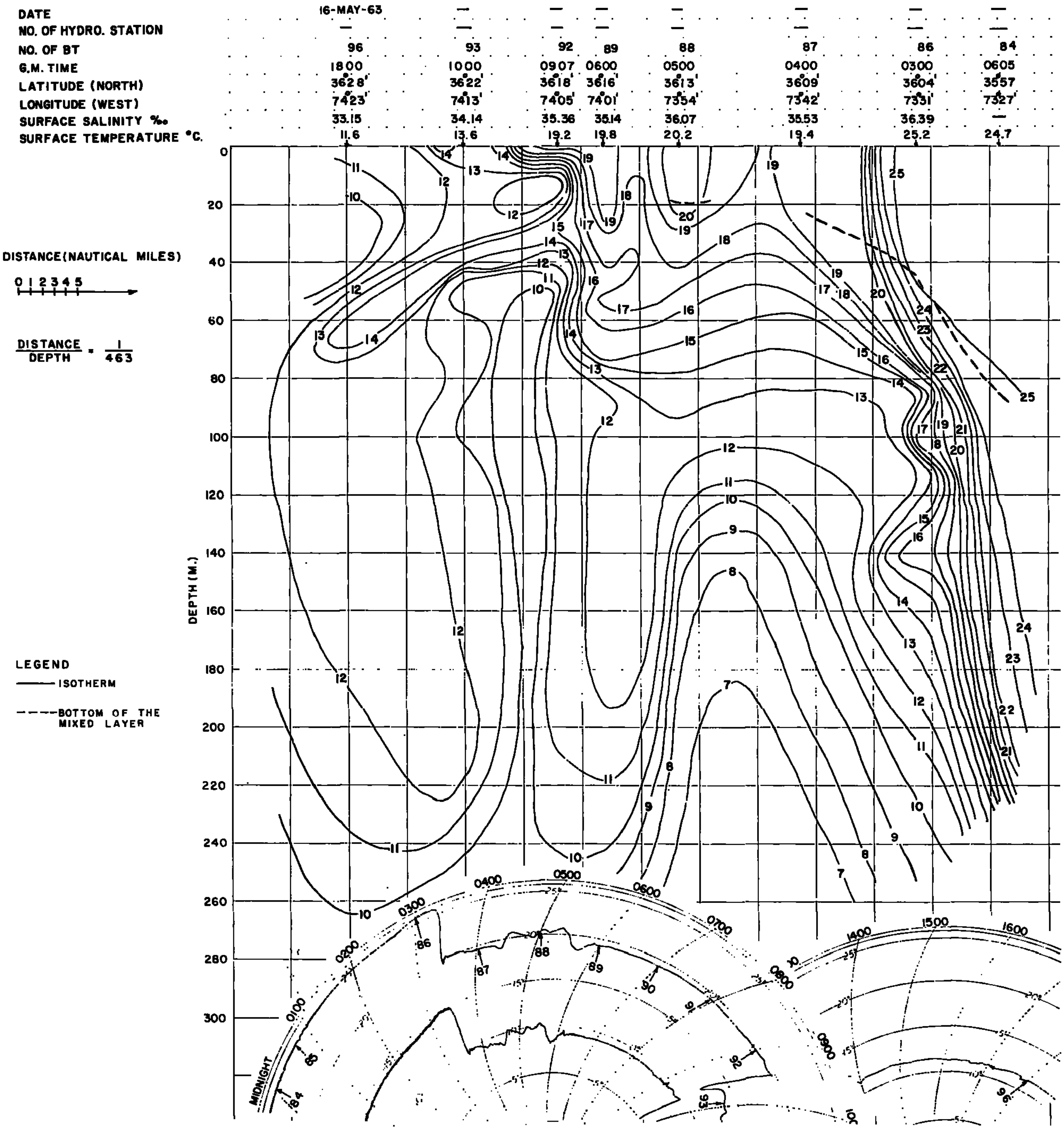

FIGURE 11.—Transect I—Section 9, May 16, 1963. (*See* caption for fig. 3.)

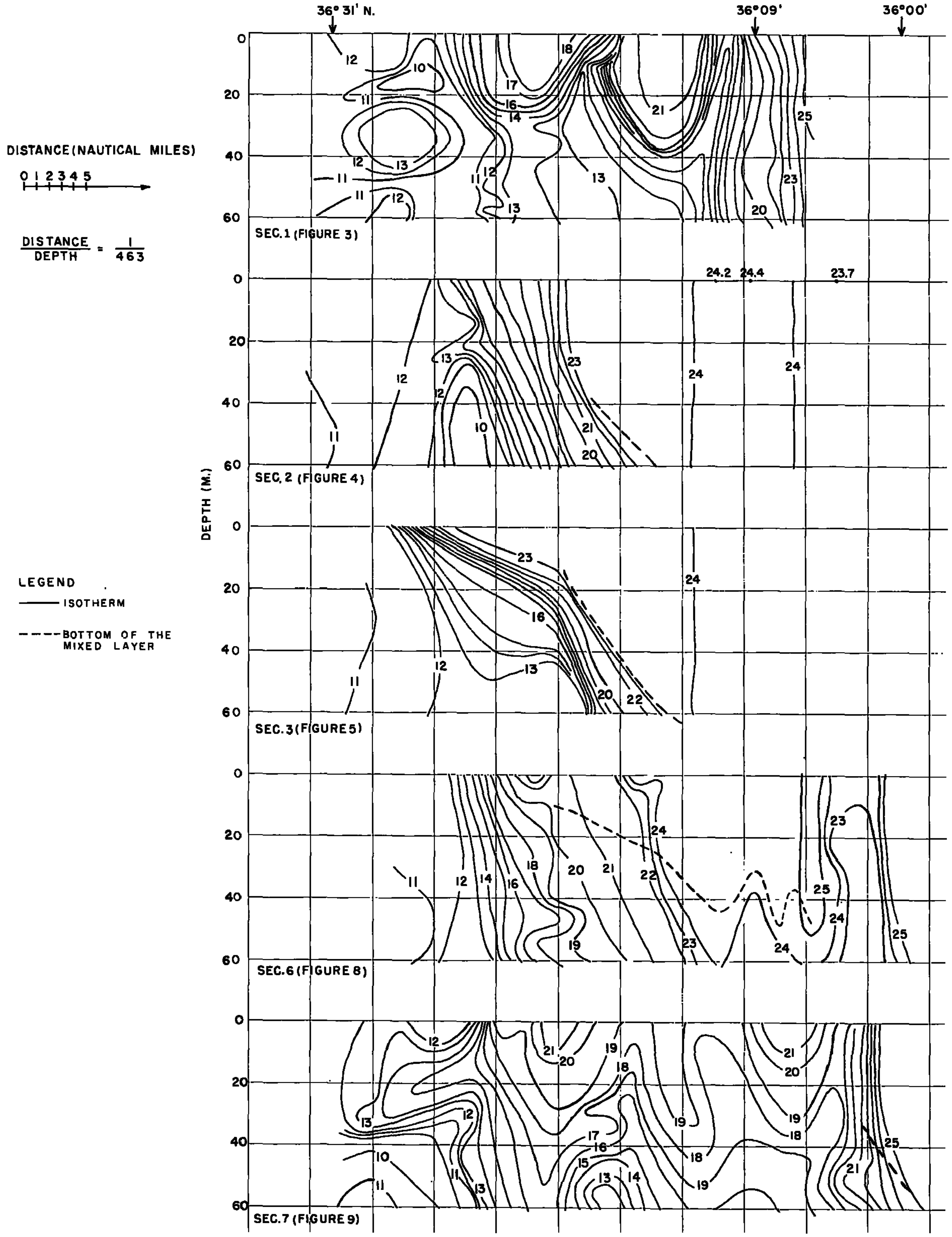

FIGURE 12.—Sections 1, 2, 3, 6, and 7 of transect I, surface to 60 m., replotted with corresponding geographical points in approximate vertical alignment.

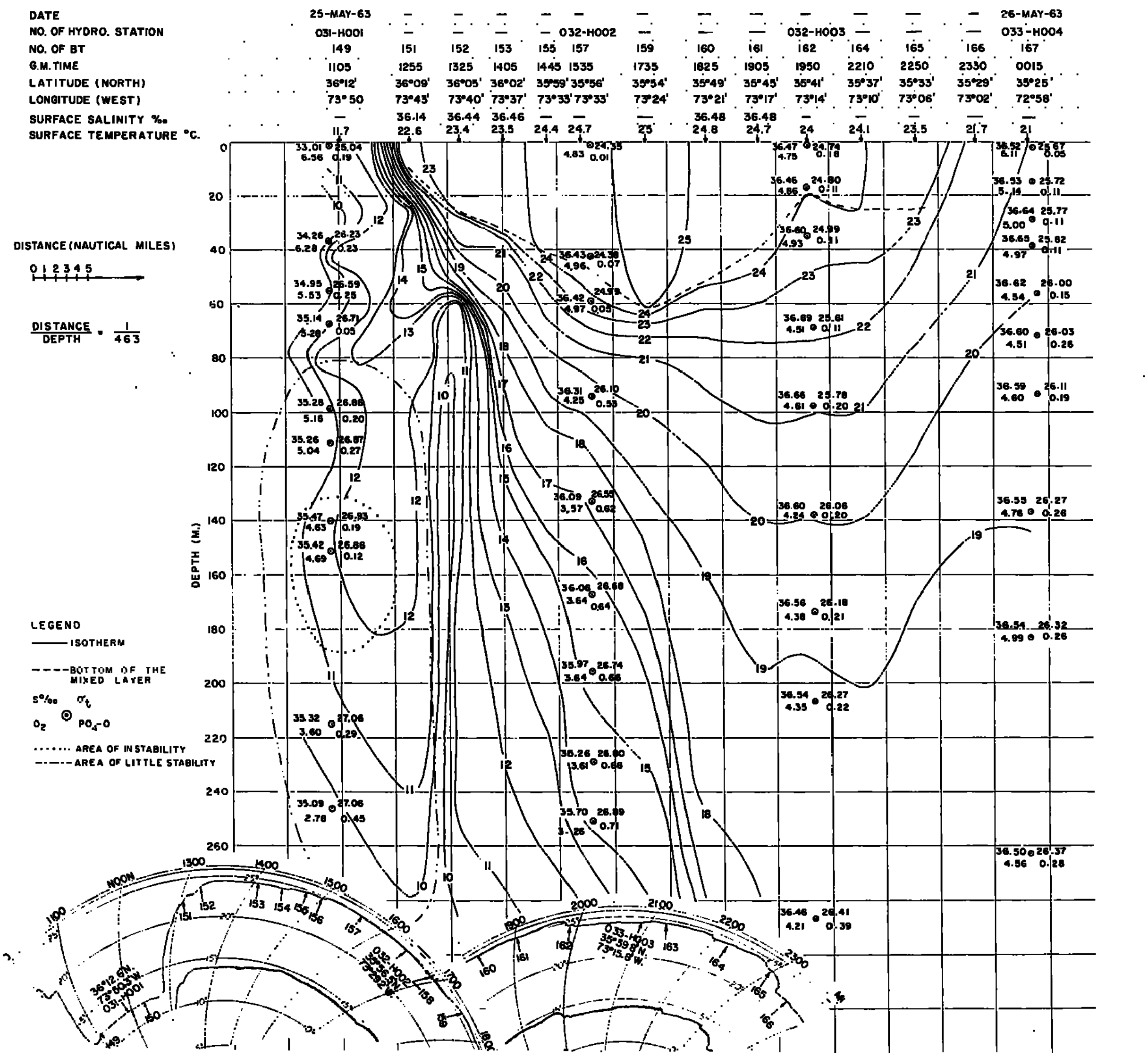

FIGURE 13.—Transect I—Section 10, May 25, 1963. Vertical temperature profile and thermograph record of surface temperatures. Thermograph temperatures greater than 25° C. are read from the lower of the two traces by adding 10° C. to the individual values. Bathythermogram numbers appear along the surface temperature trace to show the times of the casts. Data on salinity, density, dissolved oxygen (ml./l.), and inorganic phosphate (μg.-at./l.) are plotted on the vertical profile but not contoured.

the left boundary of the Gulf Stream in each transect is indicated in figure 1 by unbroken straight lines. The observed range of positions of the boundary on transects I and II is indicated by two parallel dashed lines. The mean and range of the boundary positions along transect I are based on observations during 14 crossings between May 10 and June 6, 1963, and along transect II on 5 consecutive crossings between May 31 and June 5, 1963. The range is not given along transect III because only three sections were made across the boundary (in 2 consecutive days).

Data are inadequate for the evaluation of horizontal movement of the left boundary or of the warm core between the transects. (Data from the only run along the boundary from transect II to transect I did not show significant meandering.) It is reasonable, nevertheless, to make inferences from transect I data,

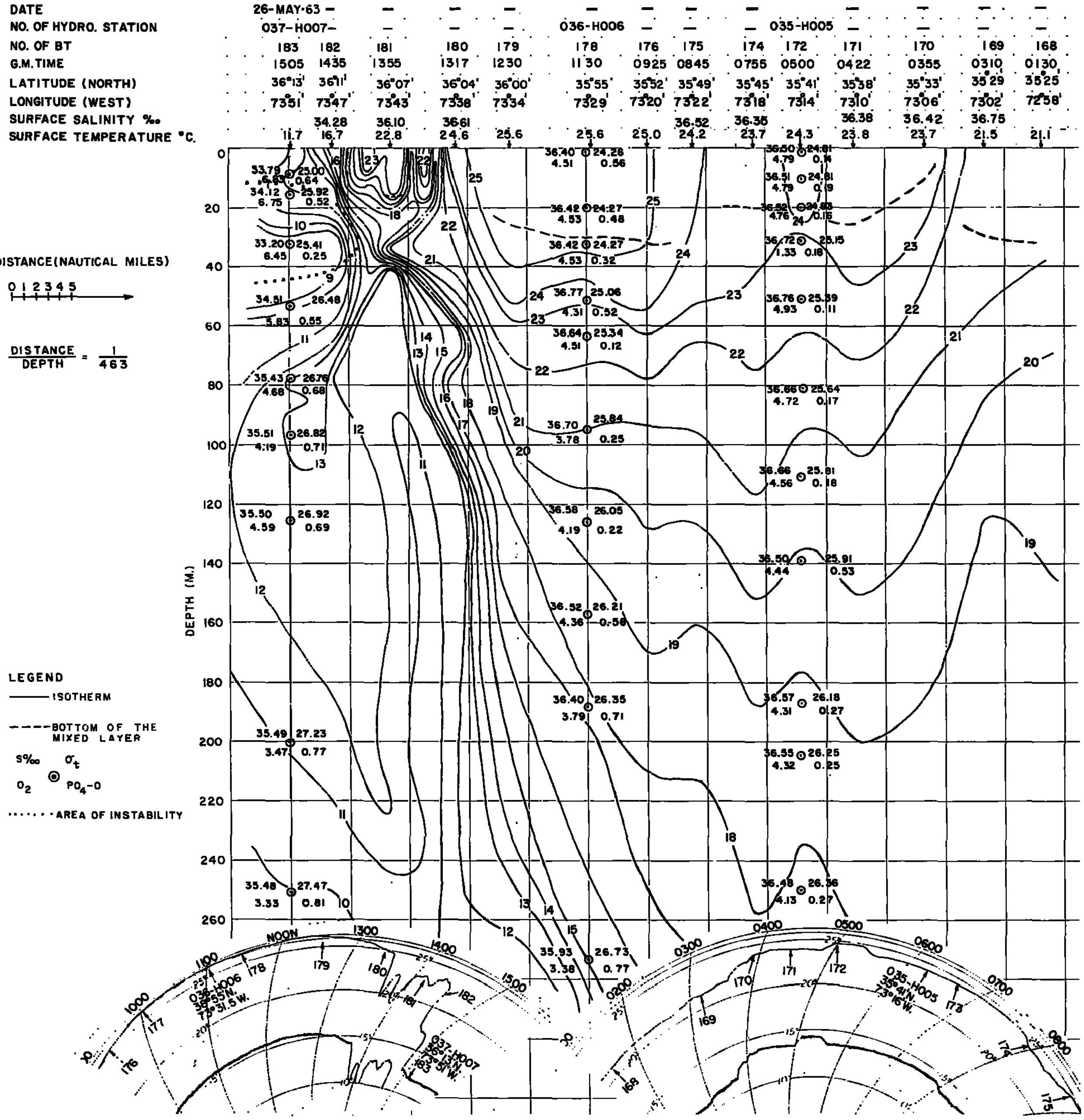

FIGURE 14.—Transect I—Section 11, May 26, 1963. (*See* caption for fig. 13.)

in which the position of the left side of the warm core oscillates by about 10 miles (18.5 km.) on either side of the mean (dotted line, fig. 1). The left boundary of the Gulf Stream was not more than 10 miles right of its mean position in any of the sections but was about twice as far left in one section.

The observations along transect I indicate that the oscillation of the left boundary of the Gulf Stream and the width of the intermediate zone were not directly interdependent. Formation of the intermediate zone did not necessarily depend on oscillation of the boundary—oscillation may presumably occur when the intermediate zone is nonexistent. Some boundary oscillations, however, did seem to be con-

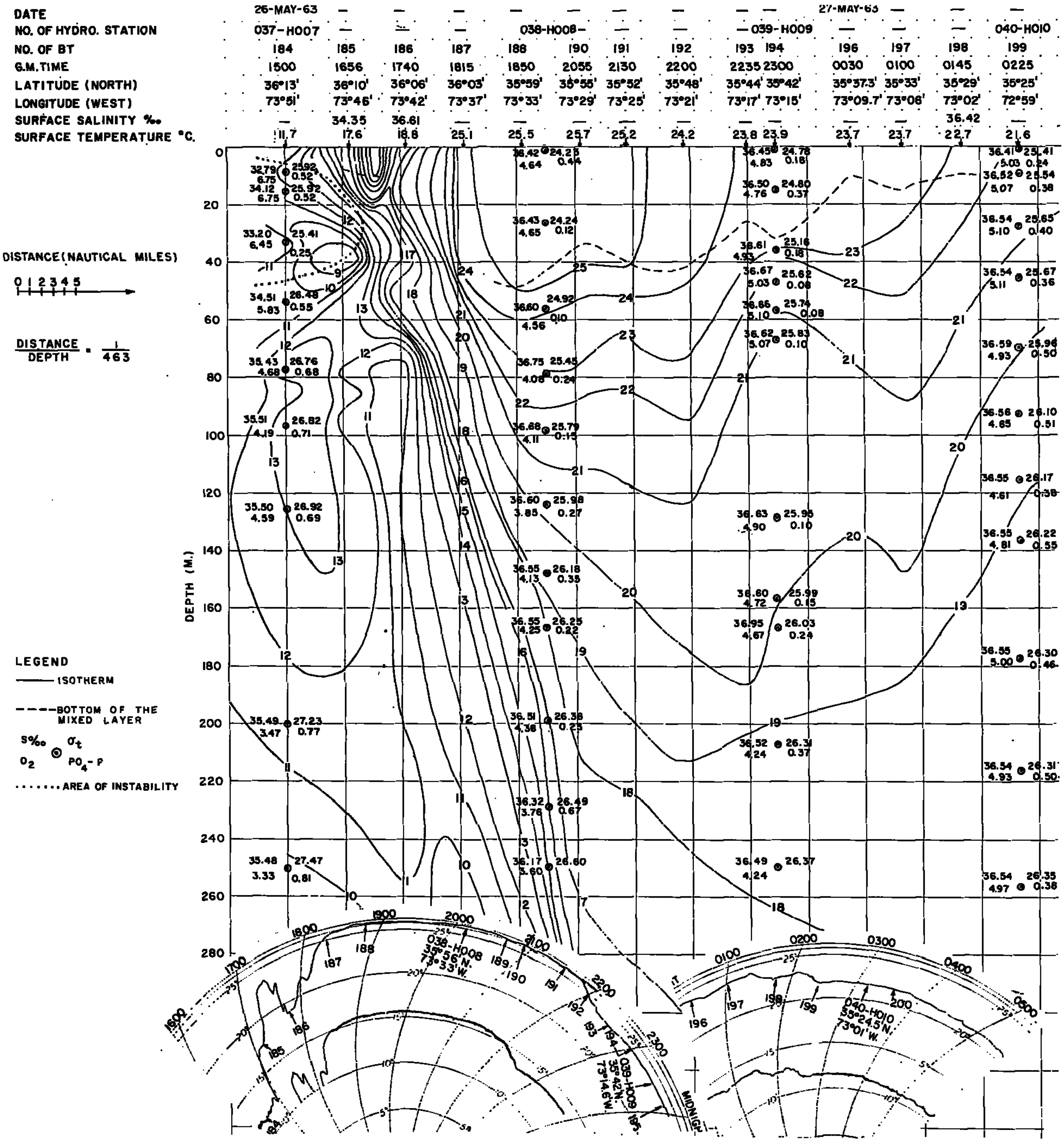

FIGURE 15.—Transect I—Section 12, May 26, 1963. (*See* caption for fig. 13.)

nected with development of an intermediate zone. The boundary during a well-developed intermediate zone was found right of its mean position, but the boundary during a weakly developed intermediate zone was left of its mean. Along transect II, the limited number of observations suggests that the pattern of oscillation was similar to that in transect I.

WARM CORE OF THE GULF STREAM

The core of warmest water was found at or near the left boundary of the Gulf Stream. The

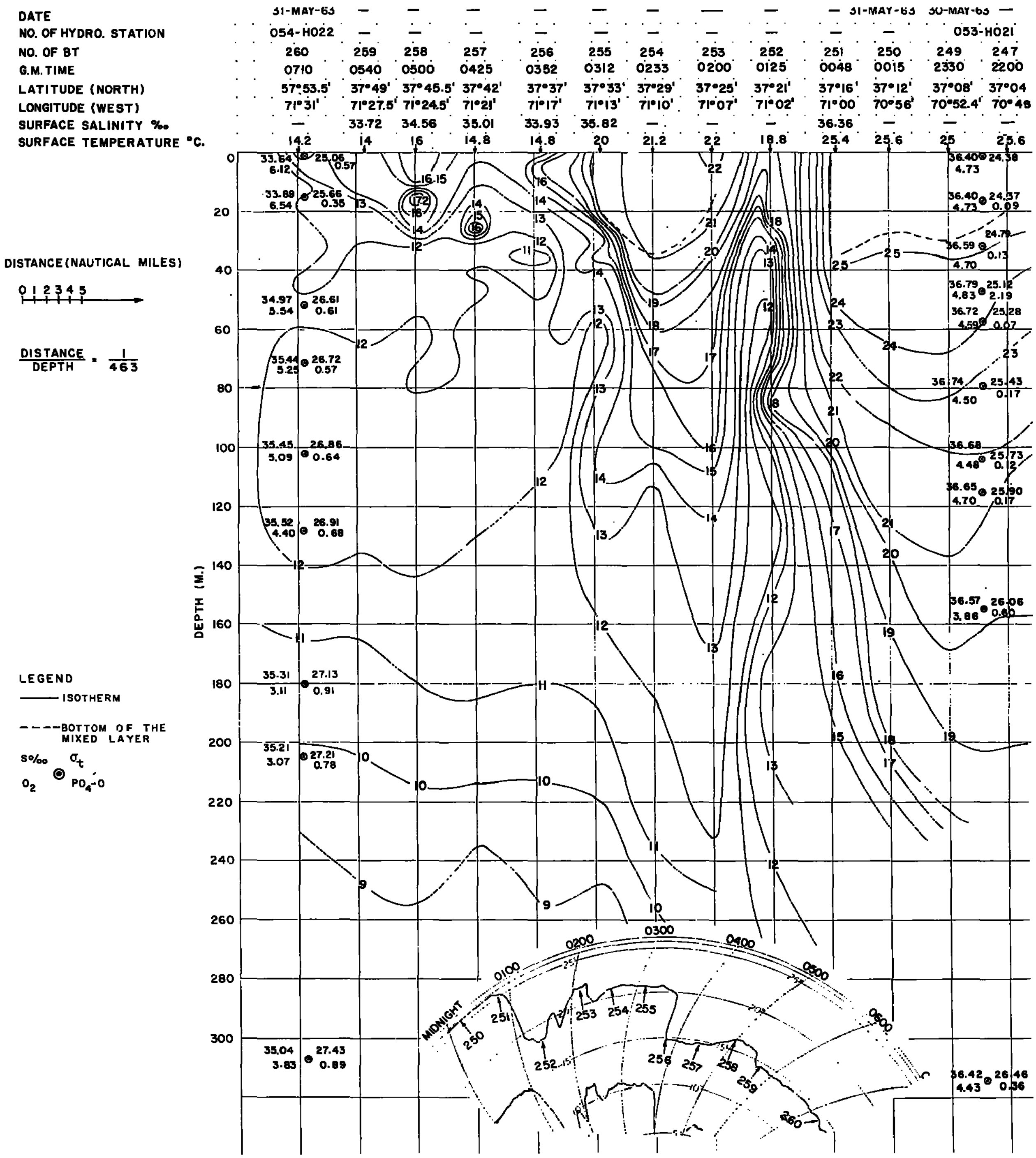

FIGURE 16.—Transect II—Section 13, May 31, 1963. (*See* caption for fig. 13.)

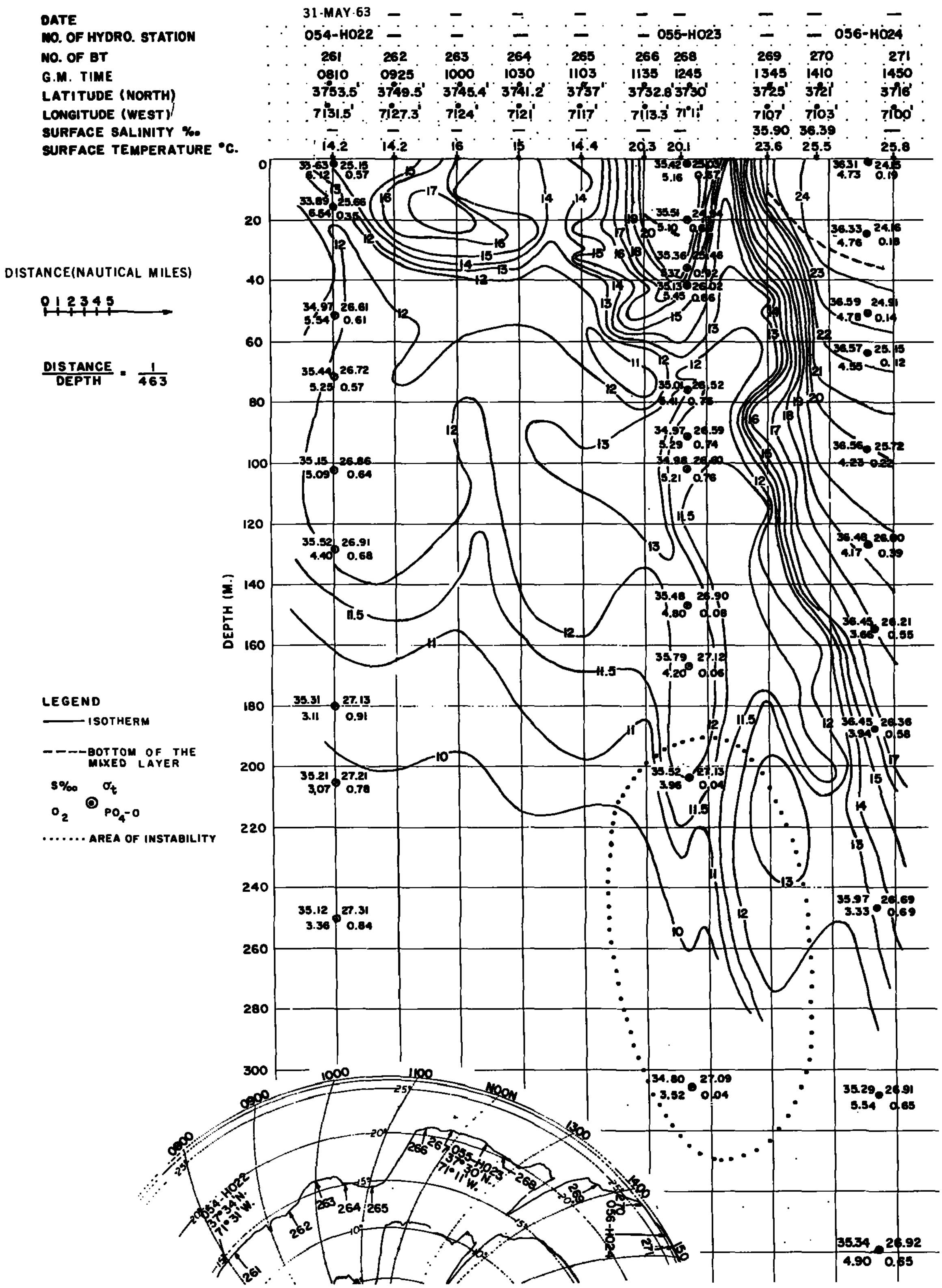

FIGURE 17.—Transect II—Section 14, May 31, 1963. (*See* caption for fig. 13.)

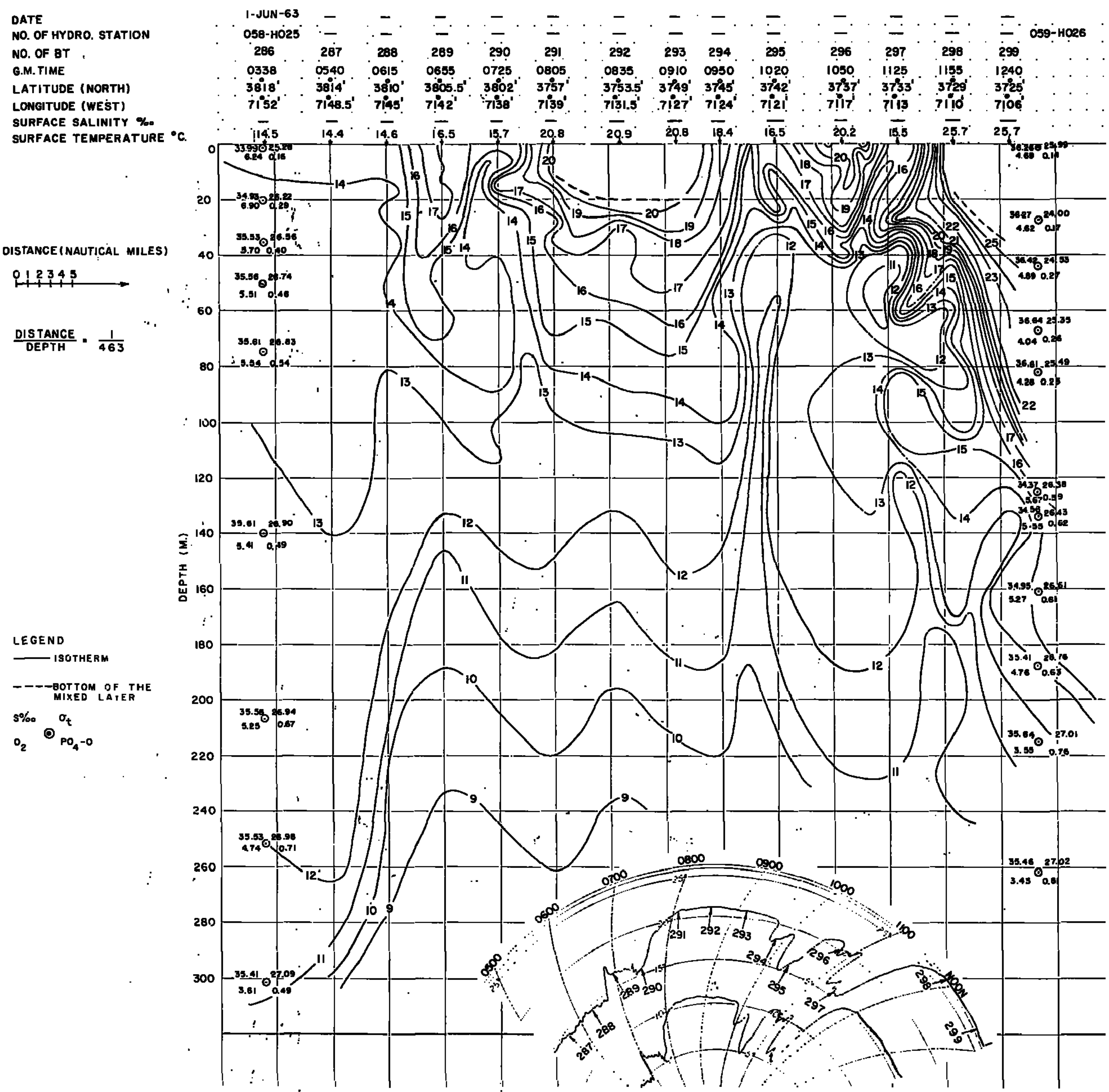

FIGURE 18.—Transect II—Section 15, June 1, 1963. (*See* caption for fig. 13.)

warm core is defined as that part of the Gulf Stream which was warmer than 24° C. in the period covered in this report.

RIGHT BOUNDARY OF THE GULF STREAM

The right boundary of the Gulf Stream is defined here as a strong horizontal temperature gradient at the surface as illustrated in figure 2 between BT's 367 and 366. The right boundary of the Stream was crossed three times along transect I. The mean position is indicated in figure 1 by a dash-dot line. Crossings were within a 2-day period, and the boundary was displaced slightly to the south on the third crossing. On the first crossing, the boundary appeared on the surface temperature record between BT's 165 and 166 (fig. 13); on the second crossing, between BT's 169 and 170 (fig.

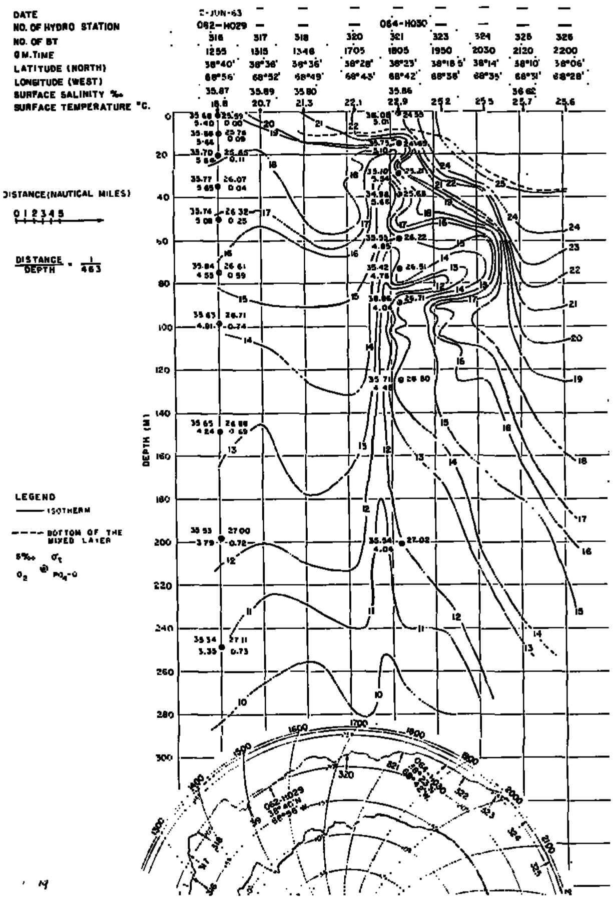

FIGURE 19.—Transect III—Section 16, June 2, 1963. (*See* caption for fig. 13.)

14); and on the third crossing, between BT's 197 and 199 (fig. 15).

The right boundary was crossed only once along transect II. Unfortunately, no surface temperatures are available because the recorder was temporarily out of order. Since the temperature difference between the Sargasso Sea and the Gulf Stream was 4° C., the boundary may have been even more distinct than along transect I.

The right boundary was crossed only once along transect III also; the crossing is shown on the surface temperature record between BT's 358 and 359 (fig. 21). The isolated peak on the trace represents an occasion when the ship was steered back and forth quickly across the boundary along legs about 200 m. long. At this time, the boundary was distinctly indicated by surface conditions. The sea was choppy on the Gulf Stream side but relatively smooth on the Sargasso Sea side, with no zone of transition—just a sharp line.

The right boundary was crossed again at lat. 37°12′ N. and long. 69°23′ W., while the vessel traveled from transect III to transect II (fig. 1; also see surface temperature trace in fig. 2). The boundary was crossed within 5 miles (9.3 km.). Since we were running obliquely to the Stream, the actual gradient at the boundary must have been considerably steeper than indicated on the trace.

The presence of a distinct right boundary on all occasions contradicts statements in the literature on the subject, to the effect that no detectable boundary exists between the Gulf Stream and the Sargasso Sea (Iselin, 1936, 1940). Possibly, of course, the boundary is not marked in the warm season, when the temperature of the surface waters is higher in the Sargasso Sea than in the Gulf Stream. Perhaps the right boundary is more typical of conditions in winter and spring than in other seasons.

WIDTH OF THE GULF STREAM

The Gulf Stream was about 50 miles (92.6 km.) wide along transects I and II, but about 70 miles (129.6 km.) along transect III. The greater width along transect III may not have represented a greater actual width of the Gulf Stream, but only a transient deformation of its right side. A similar deformation is indicated for the same day at this location in the U.S. Naval Oceanographic Office sea-surface temperature chart.

ENVIRONMENT OF THE GULF STREAM

The Gulf Stream structure, at the surface bounded on the left and right as defined in the previous section, consisted of a warm core flanked by rather small horizontal temperature gradients of varying widths. The warm core extended to depths of 60 to 80 m. over a width of 25 to 35 miles (46.3–64.8 km.). Mean values are given to facilitate comparison of the surface properties of the slope water, the Gulf Stream as a whole, the warm core of the Gulf Stream, and the Sargasso Sea (table 1). The slope water values are from five stations along transects I and II. None of these five stations was entirely out of Gulf Stream influence; therefore, the values are not entirely representative of typical slope water.

TABLE 1.—*Mean values of surface properties in the Gulf Stream and adjacent water masses (Geronimo Cruise 1)*

	Temperature	Salinity	σ_t	Oxygen	PO_4–P
	° *C.*	°/₀₀		*ml./l.*	*µg. at./l.*
Slope water	12.98	33.59	25.34	6.31	0.35
Gulf Stream (all stations)	25.01	36.42	24.41	4.76	.18
Gulf Stream (warm core stations only)	25.61	36.36	24.20	4.66	.27
Sargasso Sea	21.64	36.57	25.49	5.08	.15

The water masses of the slope water, Gulf Stream, and Sargasso Sea were distinctly different in all properties, both at the surface and in the subsurface layers. The subsurface properties left of the Gulf Stream were characteristically erratic; in the Gulf Stream and Sargasso Sea the properties tended to be regular, except for phosphate, which varied greatly to about 300 m.

INTERACTION OF THE SLOPE WATER AND THE GULF STREAM

The present data draw special attention to the transient nature of the intermediate zone at the left side of the Gulf Stream. In the first section with oceanographic stations (transect I, fig. 13), one sharp boundary appears where the surface temperature increased from 13° to 22° C. in about 2.5 miles (4.6 km.); the intermediate zone was almost nonexistent at the surface. In the transect of 24 hours later (fig. 14), the situation has changed drastically: the intermediate zone extends over 15 miles (27.8 km.), and two surface temperature boundaries are distinct. The variability of the width of the intermediate zone and its intermittent disappearance tend to demonstrate that its existence was the result of interaction between two water masses.

INTERACTION SYSTEMS

The intermediate zone has, of course, a vertical dimension. In the following interpretation, therefore, it is convenient to use the term "interaction system" for the entire volume of intermediate water.

The dimensions, shape, and internal structure of the interaction system shown in figures 3 and 4 change and transform rapidly, but the formation of the system seems to have a certain repetitive pattern. In figure 3 the intermediate zone is well developed. The two boundaries, enclosing the intermediate zone, are clearly marked on the surface temperature record. Temperature increases sharply by 7° C. at the slope water boundary, between the BT numbers 4 and 5. The intermediate zone is composed of two cold-water belts and two shallow warm-water cores. At the boundary between the intermediate zone and the Gulf Stream the temperature rises in two steps from about 15° in the cold belt to 24° in the Gulf Stream. A complicated pattern of the interaction extends in this section to about 230 m.

When the next section (fig. 4) was taken 2 days later, the boundary structure had changed. The intermediate zone with shallow currents and cold-water bands disappeared. Only one boundary was at the surface between the slope water (temperature 11.6° C. and salinity 33.75°/₀₀) and the Gulf Stream (temperature 23.2° C. and salinity 36.29°/₀₀); within the warm core the temperature was 24.2° C. and salinity 36.41°/₀₀. Some traces in the interaction system can be observed in the subsurface. The surface temperature trace is relatively smooth along the steep temperature gradient in the boundary zone.

In the following section (fig. 5) the boundary was crossed about 6 hours later. The boundary zone is narrower than in the previous section. The temperature changes from 11.8° C. to 23° C. in about 4 miles (7.4 km.), and the surface temperature trace rises almost vertically, but, in general, the boundary structure does not change between the two sections. A large mass of 12° C. water is enclosed by cooler water in the subsurface.

The section in figure 6 shows the boundary about 5 hours later. The surface temperature trace shows a small disturbance within the boundary. The disturbance was not present in the previous section. In the subsurface the 12° C. water has been reduced in volume and has separated. A bubble of 13° C. water is at 45 m., but it is not certain whether it has been ad-

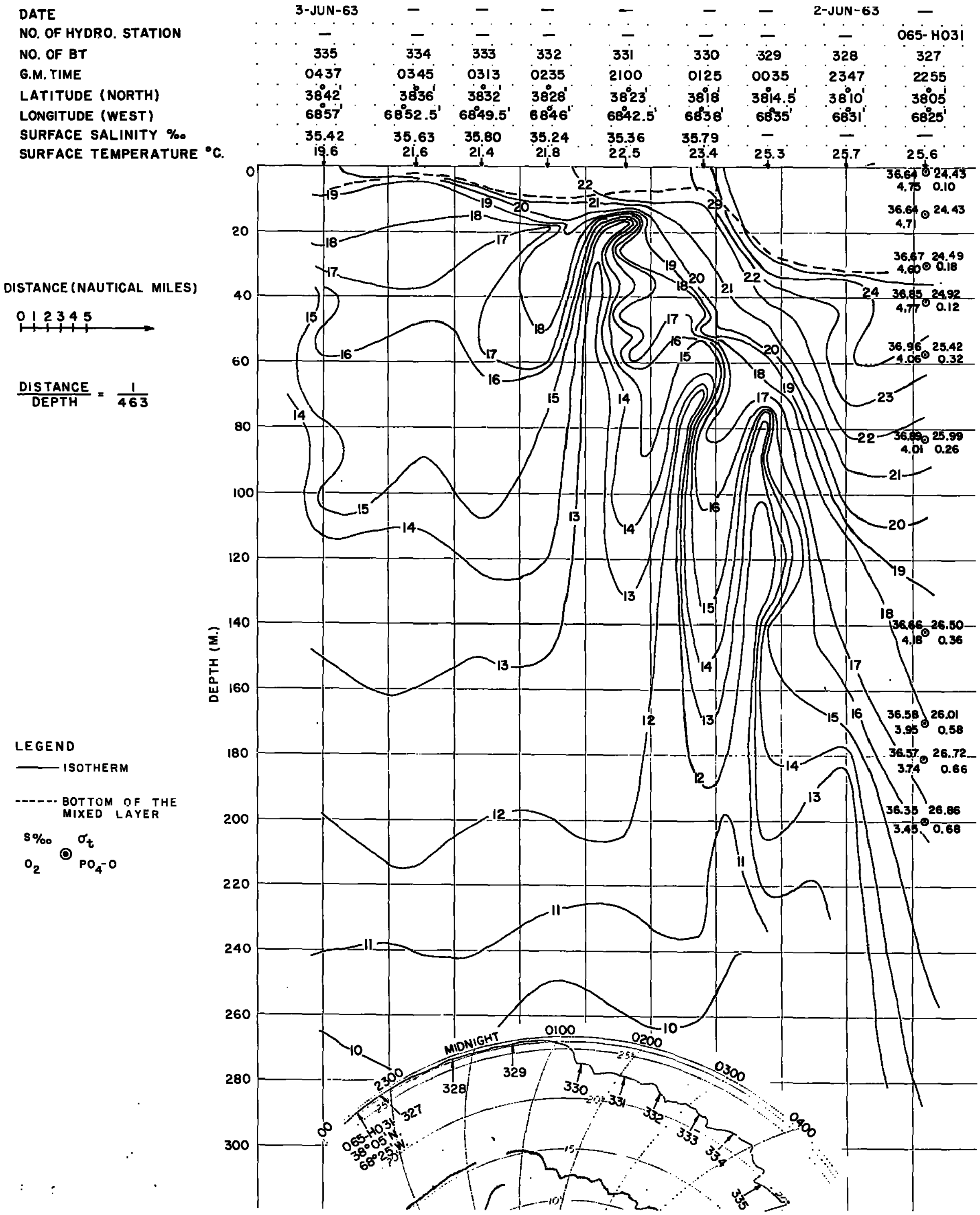

FIGURE 20.—Transect III—Section 17, June 3, 1963. (*See* caption for fig. 13.)

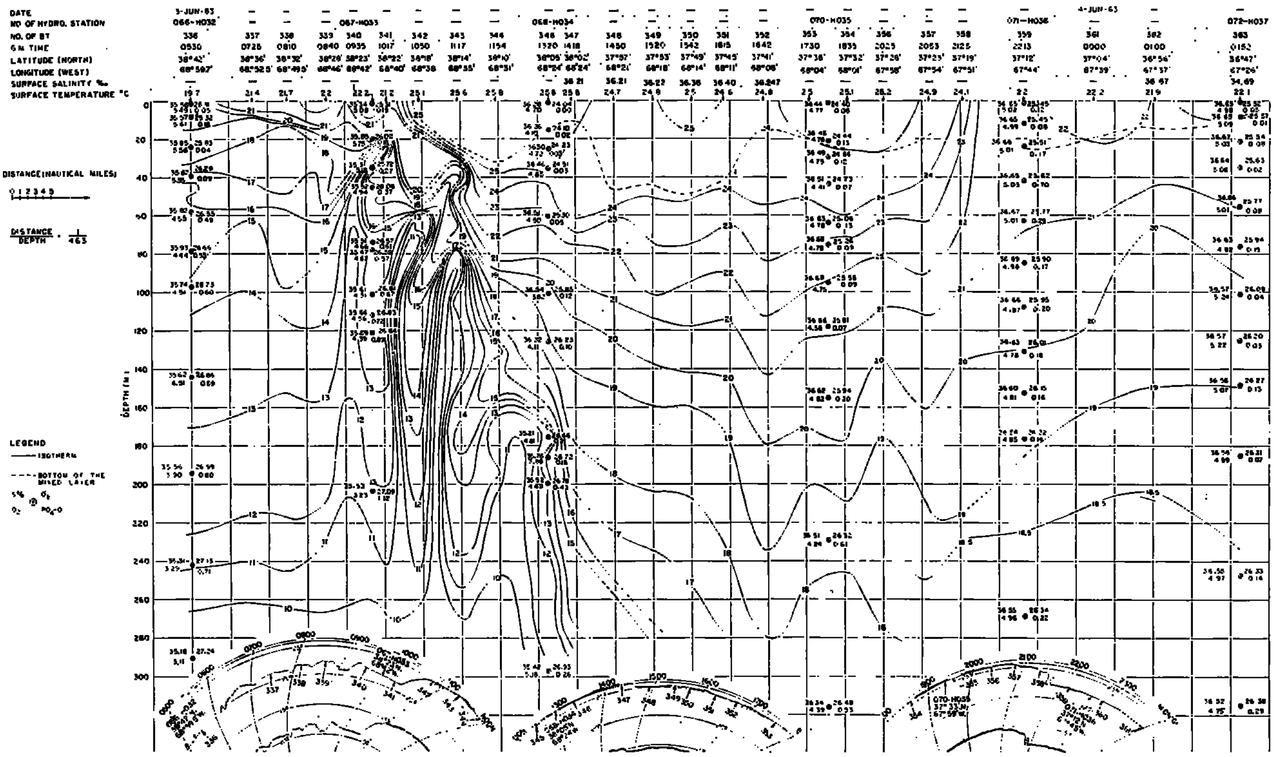

FIGURE 21.—Transect III—Section 18, June 3, 1963. (*See* caption for fig. 13.)

vected along the boundary or formed locally by occlusion of a lateral tongue of warmer boundary water.

About 7 hours later was the next crossing of the boundary (fig. 7). The boundary disturbance, which had just started in the previous section, had intensified and looked like a shallow small-scale upwelling with a cool belt very close to the Gulf Stream water. The surface temperature trace shows it as a cool-water stripe. The mass of 12° C. water in the subsurface has reduced further in volume. The warm bubble is at a shallower depth in this section than in the previous and is somewhat warmer. It may be either a new feature or a slow drifting of the same occluded warm water along the boundary. We could expect such an elongated bubble to be warmer in the center.

In the following section (fig. 8) about 5 hours later, a very large-scale process begins within the left side of the Gulf Stream. The former boundary is at about the same location, and the small-scale disturbance is still clearly marked on the surface temperature trace. A new boundary is forming 25 miles (46.3 km.) within the Gulf Stream near the velocity maximum. The cool belt at the surface is shown at the right section of the temperature record at BT number 65. The surface salinity in the cool stripe is 36.04 ‰ and, probably, is somewhat lower in its center. To the left and to the right of the cool band the surface salinities are 36.37 ‰ and 36.37 ‰. The bottom of the mixed layer is indicated by the dashed line. The cool band has no mixed layer. Apparently an intense upwelling process has been just started and is cutting off a very large portion of the Gulf Stream water from the main body of the Stream.

The next section shown in figure 9 was made about 20 hours later. The intermediate zone is about 35 miles (64.8 km.) wide and is at about the same stage of development as it was in the first section (fig. 3). The separated mass at the Gulf Stream is split into two shallow warm-water cores. The subsurface has changing jets or tongues of cold and warm water immediately

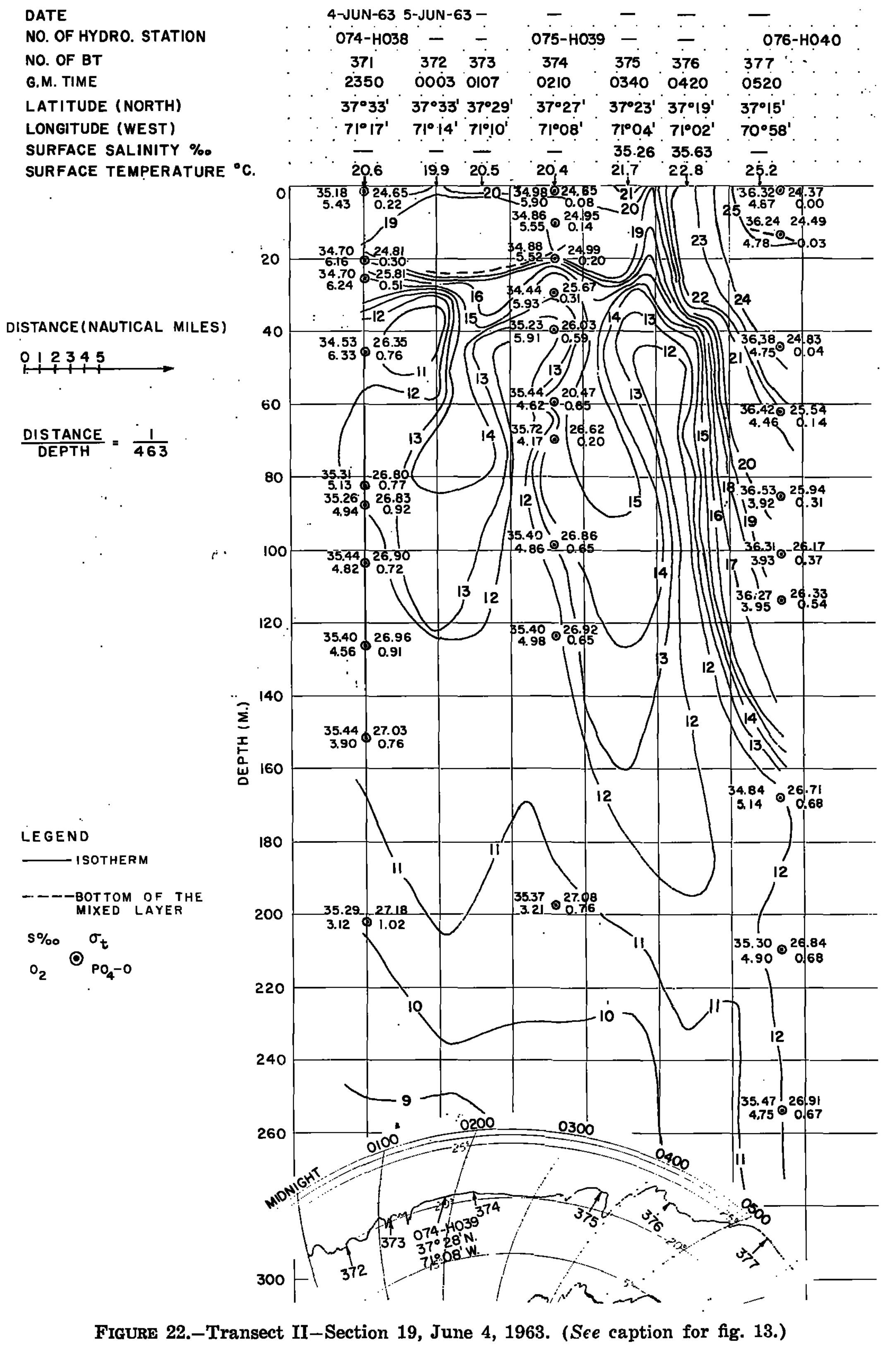

FIGURE 22.—Transect II—Section 19, June 4, 1963. (*See* caption for fig. 13.)

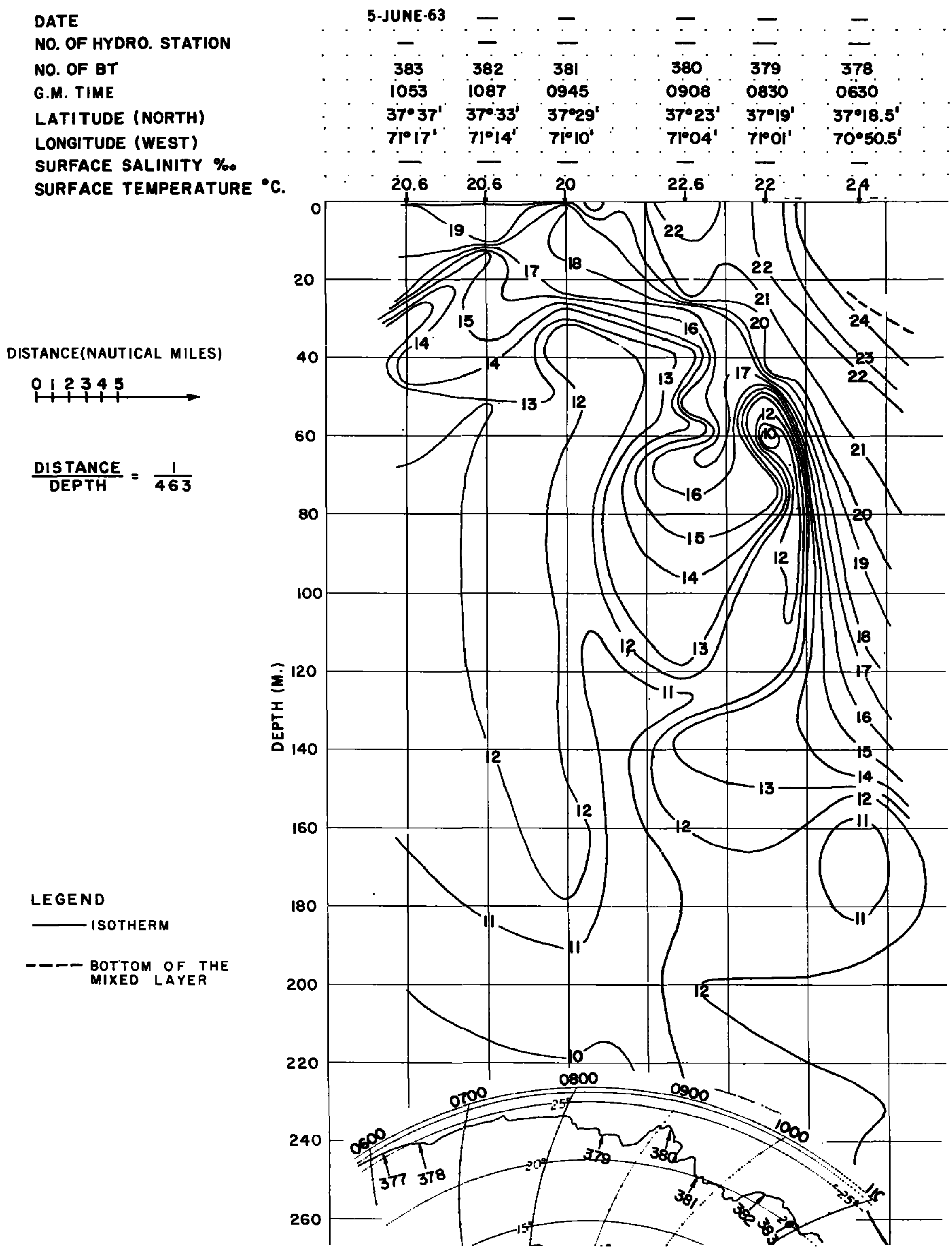

FIGURE 23.—Transect II—Section 20, June 5, 1963. (*See* caption for fig. 13.)

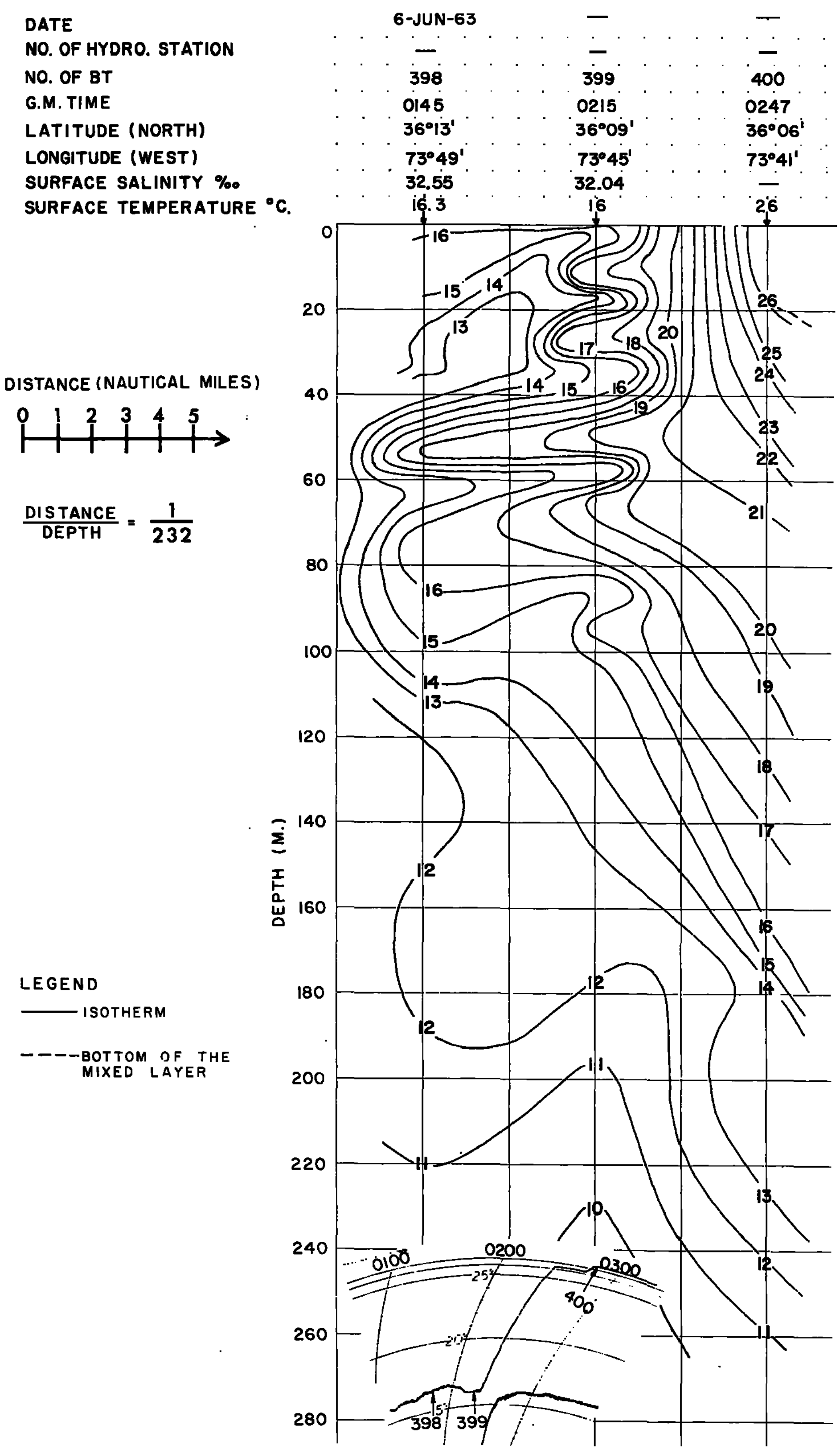

FIGURE 24.—Transect I—Section 21, June 6, 1963. (*See* caption for fig. 13.)

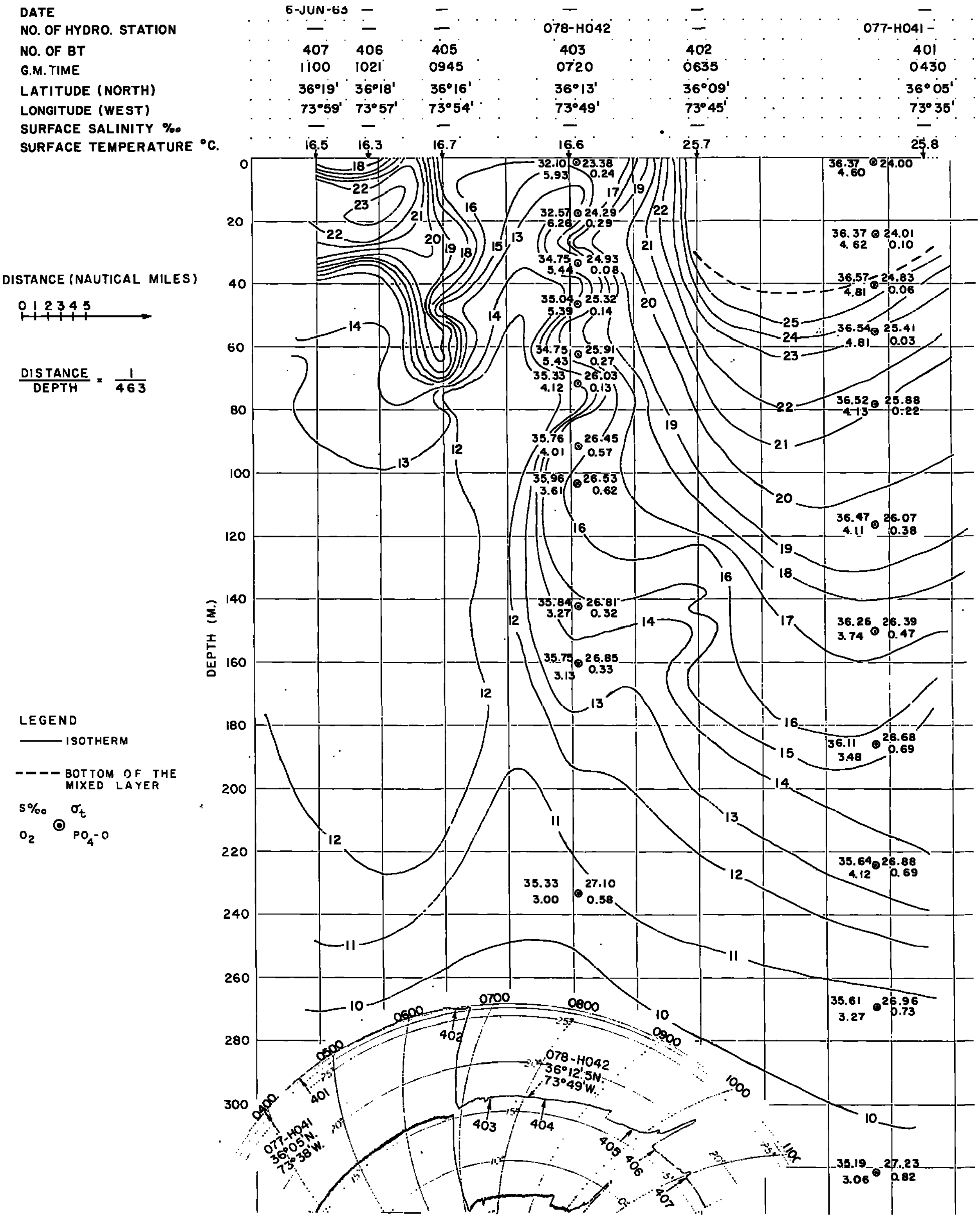

FIGURE 25.—Transect I—Section 22, June 6, 1963. (*See* caption for fig. 13.)

to the left of the slope water boundary at the surface.

The section shown in figure 10 was taken about 5 hours later, and one more section of the sequence was made 20 hours later (fig. 11). Both sections represent a dissipation stage of the interaction system which has been formed by the process shown in figure 8.

The thermal structure in figure 10 is somewhat simpler than in the previous section (fig. 9), but the two cold-water stripes, one near the Gulf Stream boundary and the other between the two shallow warm-water cores, are still very well marked on the surface temperature trace. The cold-water stripes are almost eliminated in the next section (fig. 11). The surface temperature is relatively smooth between the two steep temperature gradient zones at the boundaries on both sides of the intermediate zone.

A number of the sections indicate that the Gulf Stream boundary moved to the left during the absence of an interaction system. To illustrate this movement, the upper 60 m. of five of the sections from transect I were replotted (fig. 12), and corresponding geographic points were placed in approximate vertical alignment. (Full plots of these sections appear in figures 3, 4, 5, 8, and 9.) These sections start during one interaction cycle and end during the succeeding cycle, 4½ days later. Because the first and last of these sections represent about the same stage in the successive cycles, the time of a cycle from one strong and well-developed interaction system to another was about 4½ days (108 hours).

When the intermediate system decayed, the Gulf Stream boundary moved to the left and just one boundary remained. It became the slope water boundary when the new Gulf Stream boundary developed near lat. 36° N. The slope water boundary is almost exactly at the same location as it was in the previous cycle (fig. 3), but the new Gulf Stream boundary is about 6 miles (11.1 km.) farther to southeast and the intermediate zone is wider.

The next section across the Gulf Stream, along transect I (fig. 13), was made 10 days later. Oceanographic stations and BT's were taken in this and all the following sections. There was no intermediate zone, and the left boundary of the Gulf Stream corresponds to the situation in section 3 (fig. 5); however, this time the single boundary is about 24 miles (44.4 km.) to the southeast. Time interval between sections 3 and 10 was about 278 hours. If two cycles occurred during this time, the average period would be 139 hours.

Over half the cycle of a small interaction system was also recorded in three sections on transect I (figs. 13, 14, and 15). These figures suggest that about half the cycle was completed in 30 hours. This timing is in reasonable agreement with the 108-hour period estimated above for the cycle of a larger interaction system. Presumably the time of a cycle may vary considerably. The life span of an interaction system probably depends less on volume and shape than on the energy it contains after the separation stage.

The sections along transect II (figs. 16, 17, and 18) show stages in the maximum development of another strong interaction system. The three sections record such a small part of a complete cycle, however, that the duration of that cycle cannot be estimated.

The appearance of a rather weak interaction system can be detected in the sections along transect III (figs. 19, 20, and 21).

Altogether, six different interaction systems were observed during the *Geronimo* cruise. The mean cross-sectional area of the Gulf Stream water occluded into them is estimated to have been 1.69×10^6 m.[2]

DIRECTION AND VELOCITY OF FLOW

Beginning at the stage of development shown in figure 8, the interaction system is cut off from the body of the Gulf Stream and acts independently. It presumably flows in the same general direction as the Gulf Stream, but the cold stripe that separates the interaction system from the Gulf Stream may have some tendency toward an opposite flow. This tendency is probably only occasionally strong enough to overcome opposing flow from both sides, induced by the horizontal shearing stress. Vertically, the cold stripes and the whole interaction system sometimes seem to extend to depths greater than 300 m. but many sections indicate that the rapid change of properties occurs above 300 m. (figs. 3, 16, 17, 18, and 22).

The geostrophic velocity computed with reference to 600 m. between stations 054–HO22 and 055–HO23 (fig. 17) was 23 cm./sec. The velocity must be considerably greater in the warm-water core of the interaction system (between hydrographic station 055–HO23 and the location of BT number 266, for example). The mean geostrophic velocity, with reference to 600 m. between stations 054–HO22 and 056–HO24, was 60 cm./sec, and between stations 055–HO23 and 056–HO24, it was 128 cm./sec. Because station 056–HO24 was located in the warm core of the Gulf Stream, the data are not applicable to the evaluation of energy left in the interaction system. The 600-m. reference level may be satisfactory for stations 054–HO22 and 055–HO23 but not for station 056–HO24. Additionally, this station is on the Gulf Stream side of the cold stripe. The mean geostrophic velocity computed between stations 054–HO22 and 055–HO23 appears realistic. No great velocities within the interaction systems were observed from the *Geronimo*.

PROCESS OF INTERACTION

Apparently Gulf Stream water was supplied to the interaction systems in two principal ways. During the present observations, the dominant supply was furnished by separation. A large volume of water is separated from the left flank of the main body of the Gulf Stream —for example see figure 8.

A supplementary supply of water was by injection. Tongues of warm and cold water alternating vertically extended over a considerable horizontal distance (fig. 24). The injections tended to be moderate to weak when the main interaction system was strong (figs. 8 and 16); conversely, the injection tongues tended to be actively developed when the main interaction system was nearly dissipated (figs. 10 and 11). A general idea of the dimensions of the warm-water tongues can be obtained from a profile based on BT observations along the slope water of the left boundary of the Gulf Stream, between transects I and II (fig. 26). The figure, which covers a distance of 140 miles (259.3 km.), shows one well-developed, warm-water tongue and a few cold tongues. The well-developed tongues were about 30 miles (55.6 km.) wide (parallel to the Gulf Stream boundary) and about 40 m. thick (vertical dimension) near the base. Their average projection was about 8 miles (14.8 km.) in the direction normal to the boundary, as evaluated from 11 well-developed examples in various sections. Gulf Stream water was not a contributing factor to numerous other tongues that seemed to have developed within the interaction system after separation (figs. 9 and 10).

DEVELOPMENT AND DISSIPATION

Two principal questions may be asked regarding the interaction systems; How or why do they develop, and what happens to the water mass separated from the Gulf Stream? When an interaction system had dissipated at the surface—whatever its dimensions or character —there remained just one sharp surface boundary between the slope water and Gulf Stream (figs. 5 and 13). It seems, however, that in depths from about 40 to 200 m., the interaction systems persisted for longer periods; possibly they never decayed completely. The sequence shown in figures 4 through 8 reveals that the remnants of an old interaction system appear to be absorbed by a new one. If volumes of water as large as those involved in interaction systems are disposed of by absorption within the neighboring water masses, perceptible changes in the character of these masses could be expected. Yet in our repeated sections along transect I (in a 1-month period), even though several interaction systems developed and dissipated, no appreciable change of properties was observed in the adjacent Gulf Stream and slope water. A small rise in temperature in the slope water can be attributed to heating as the warming season progressed. Slope water was less distinctly uniform at transect II than at transect I, but because the observation period was comparatively brief, no definite conclusions can be reached about the persistence of properties.

The slope water was warmer—by about 2° to 3° C.—at transect III than at transect I. The multistream structure of the Gulf Stream as represented by Fuglister (1951) was probably absent at transect I, but may have been start-

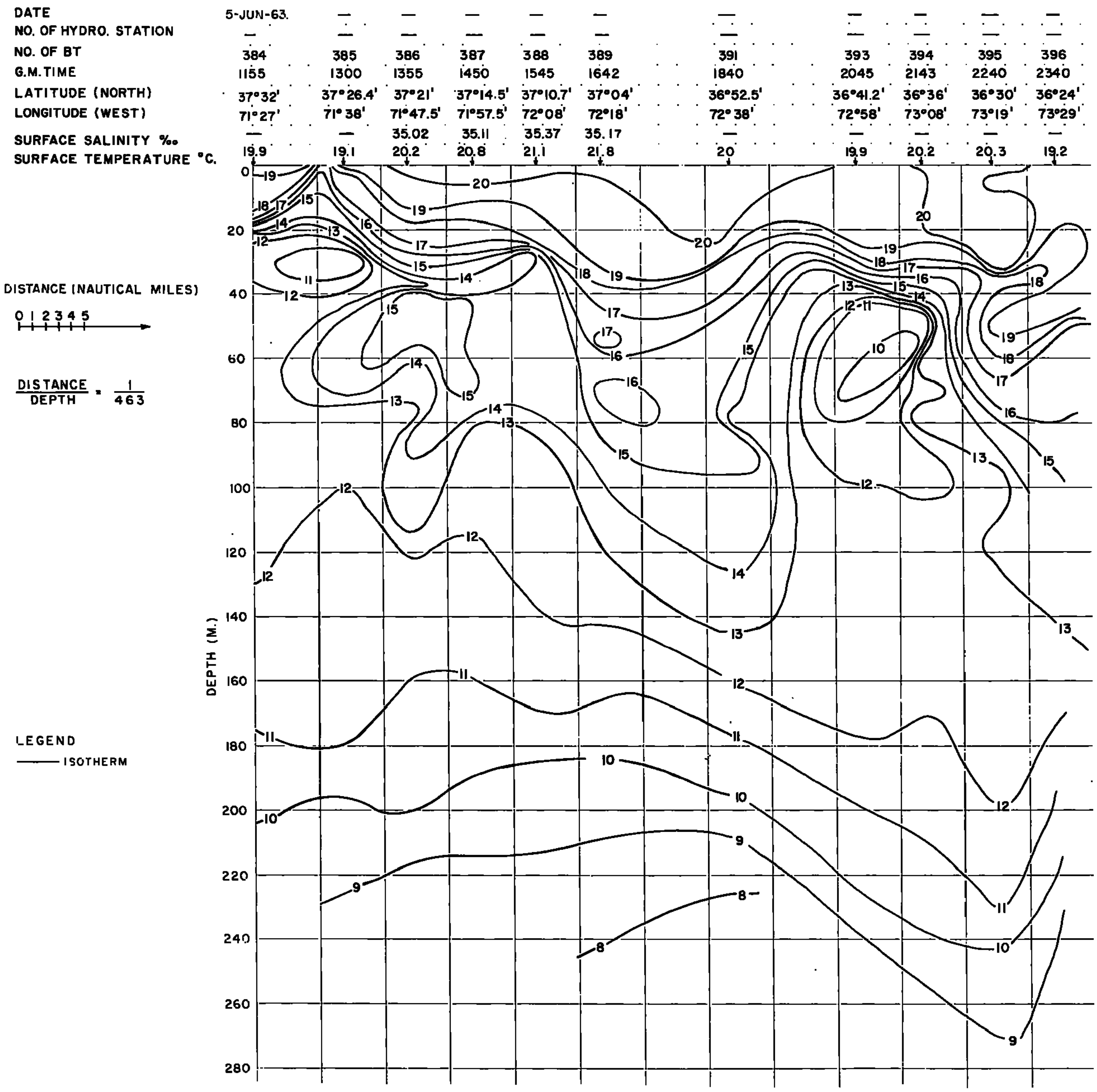

Figure 26.—Vertical temperature profile along the left boundary of the Gulf Stream between transects I and II.

ing to develop in the area between transects II and III. Thus, the likelihood exists that, in the process of dissipation, at least part of the mass of the interaction systems seen in the general area of transects I and II was channeled into secondary streams, and that these streams developed farther downstream into a multistream complex.

RETURN OF MIXED WATER TO THE GULF STREAM

A considerable part of the mass of a dissipating interaction system may be returned to the main body of the Gulf Stream at deeper levels than its point of origin. This assumption is supported by the fact that water properties in the interaction systems at depths of about

120 to 170 m. were generally the same as within the left side of the Gulf Stream at depths of 300 to 600 m. This similarity is illustrated in figures 27 to 30, which show temperature-salinity curves for the oceanographic stations made in sections 10, 12, 13, and 19. Coincidence of properties started at about $\sigma_t = 27.0$ and continued to the end of the curves (a little below 600 m.) where the approximate value is $\sigma_t = 27.8$. (The properties at 600 to 700 m. in the right side of the Gulf Stream and in the adjacent Sargasso Sea were entirely different—see the T–S curves of stations 051–HO19 and 052–HO20 in figure 27.)

The mean upper level of water with coinciding properties, computed from all available sections, was 355 m. for the left side of the Gulf Stream and 154 m. for the interaction systems. The horizontal distance between the generation area in the interaction systems and the locations of similar water in the Gulf Stream was 15 to 40 miles.

Most of the interchanging cold and warm tongues observed in the boundary area and in the interaction system were stable. When unstable situations do occur in the ocean, they are usually of short duration and it is difficult to obtain data on their frequency and the volumes. Unstable mass distributions may be created either by caballing or by rapid overflow of water of greater density over water of lesser density in the process of strong, lateral mixing. Oceanographic stations 031–HO01, 037–HO07, and 055–HO23 illustrate such unstable situations (figs. 13, 15, and 17). The instability, even if very limited in volume, was evident in 3 out of the 10 stations for which salinity data were obtained in the intermediate zone, whereas the total number of oceanographic stations was 42. The proportions may indicate that volumes of water exhibiting unstable mass distribution frequently occurred but lasted for only a brief period. Certainly errors in the data have to be considered; however, the three cases of instability occurred in the zone of intense interaction and none was outside of that zone. This fact indicates that the unstable situations were probably real.

ZONES OF CONVERGENCE AND DIVERGENCE

The left side of an interaction system is a zone of convergence with a rather permanent downward motion. When an interaction system dissipates, the convergence zone may be expected to move close to the left side of the Gulf Stream boundary. Downward motion caused by convergence is probably locally limited and too weak to transfer significant mass from an interaction system to the Gulf Stream. A superimposed momentum due to transient unstable mass distribution may, however, produce a downward flow strong enough to cover the horizontal distance between the generating and the discharging areas. The descending dense water would be absorbed by the left side of the Gulf Stream at levels about 200 m. lower than its point of origin in the interaction system. The downward motion, in turn, would intensify the surface convergence and, thus, produce a significant cross-current velocity component in the left side of the Gulf Stream.

The mean distance from the left boundary of the Gulf Stream to the location of maximum velocity in the Gulf Stream was 22 miles (40.7 km.), derived from four sections of surface velocity distribution across the current (Von Arx, 1952; Worthington, 1954). The distance between the right boundary of the Stream and the location of maximum velocity was 36 miles (66.7 km.). Outcroppings of cool water were present about 25 miles (46.3 km.) from the left boundary of the Stream, as can be seen from sections 3 and 6 (fig. 12) or by comparing sections 4 and 5 (figs. 6 and 7) with sections 6 and 7 (figs. 8 and 9). Thus, the cold stripe probably developed in the region of maximum velocity in the Gulf Stream, above the right flank of the steeply sloping isotherms, about where the 18° C. isotherm crossed the 200–m. level in section 5 (fig. 7).

Because of a strong cyclonic shear at the left of a velocity maximum and a slightly weaker anticyclonic shear at its right, a maximum horizontal gradient of the vertical component of absolute vorticity may be expected in the region of maximum velocity. The strong horizontal change in absolute vorticity may cause a tendency to diverge. If convergence in the area of interaction were intensified through the

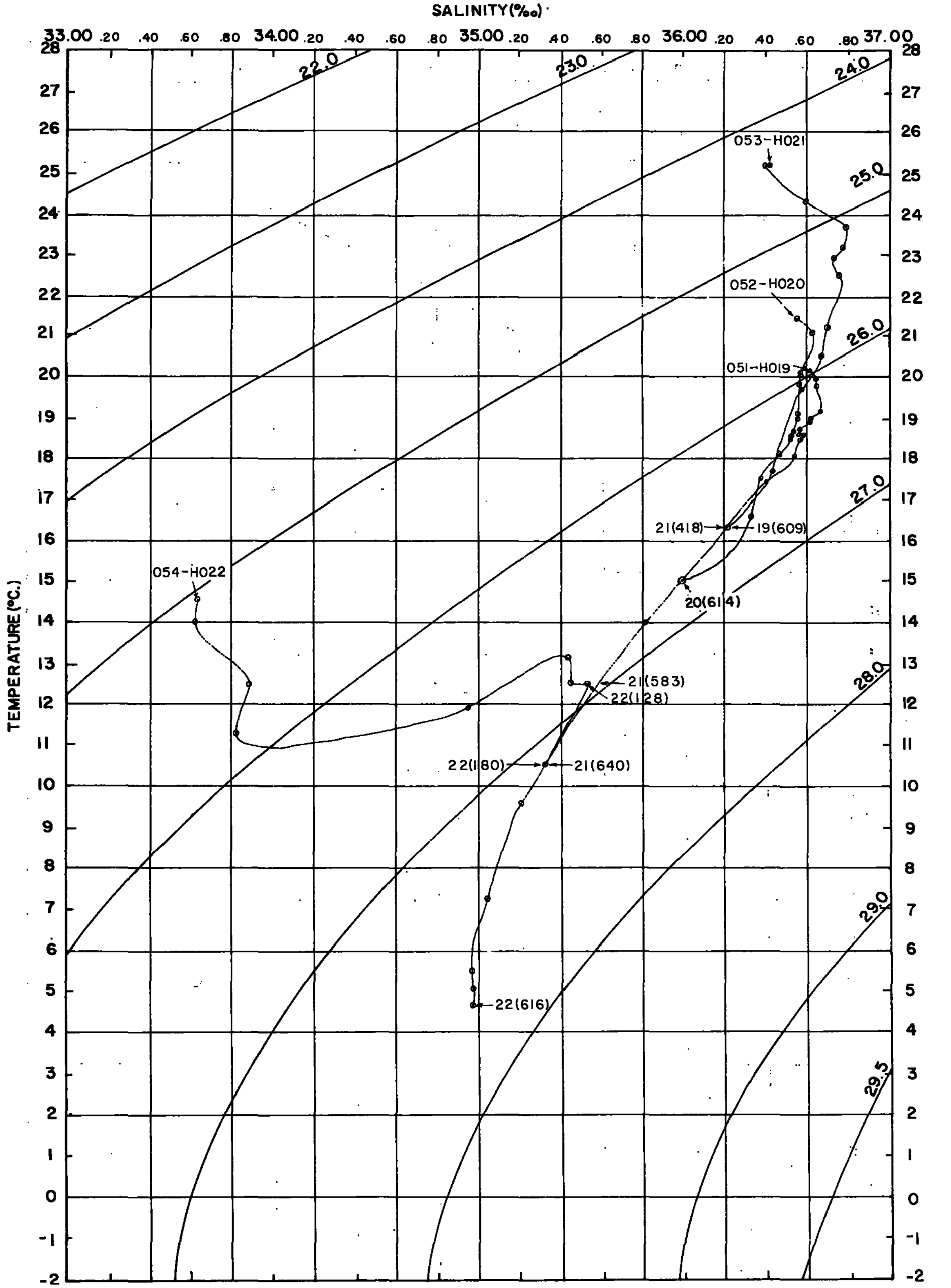

FIGURE 27.—Temperature–salinity curves along section 13. The hydrographic station number is indicated at the top of each trace. The last two digits of these station numbers also appear at points where the traces come close together or coincide. The depths of these points appear in parentheses.

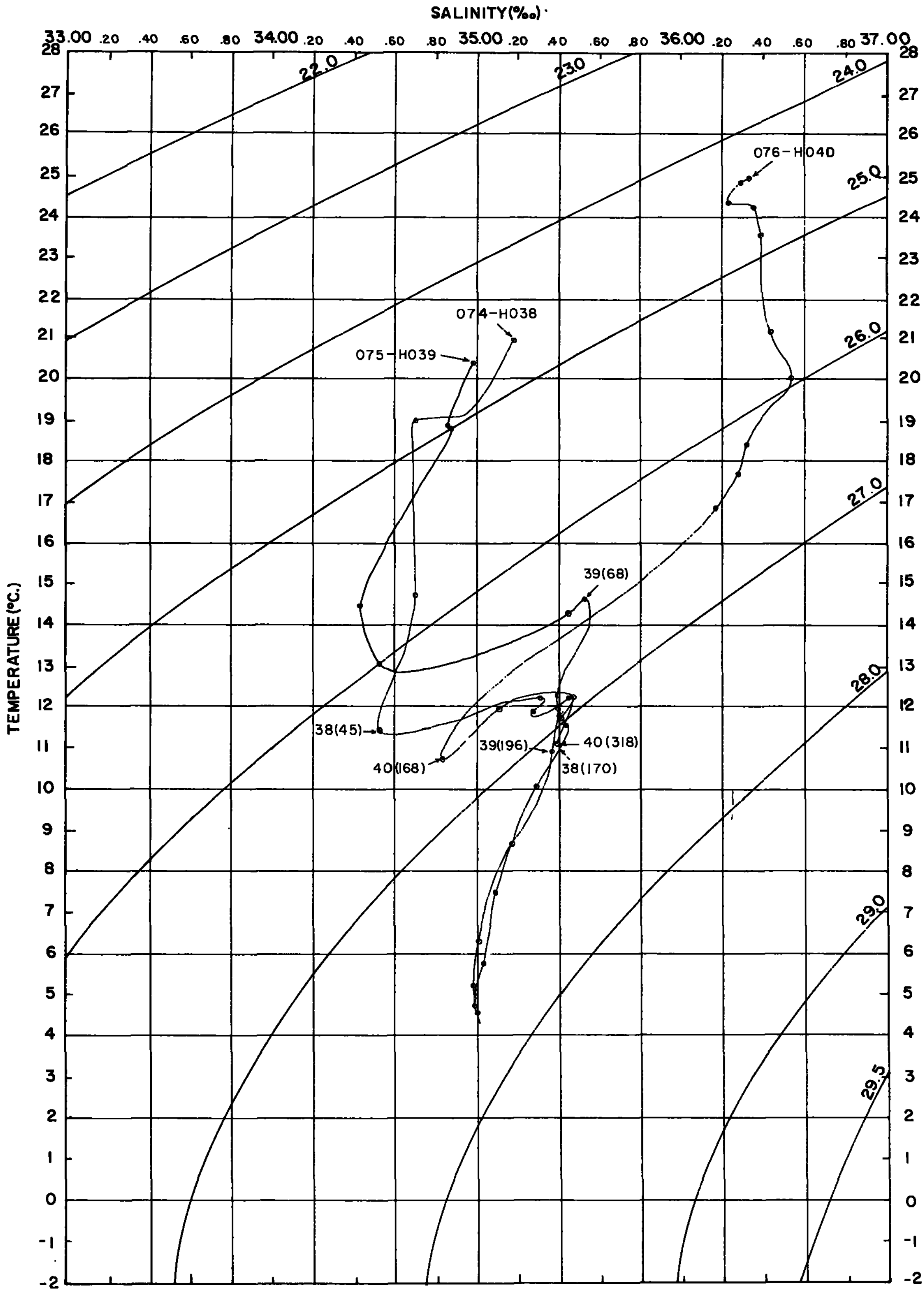

FIGURE 28.—Temperature–salinity curves along section 19. (*See* caption for fig. 27.)

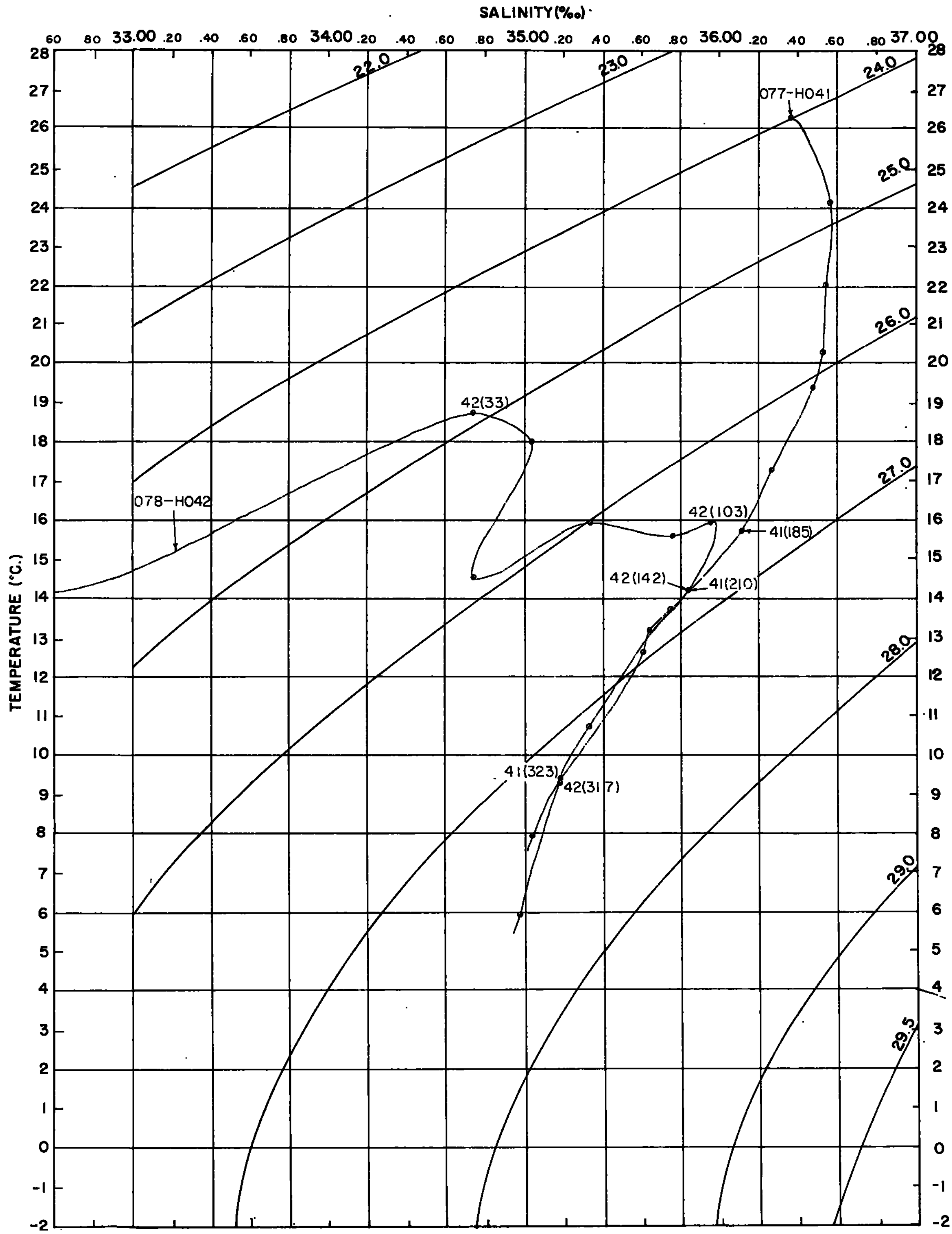

FIGURE 29.—Temperature-salinity curves along section 22. (*See* caption for fig. 27.)

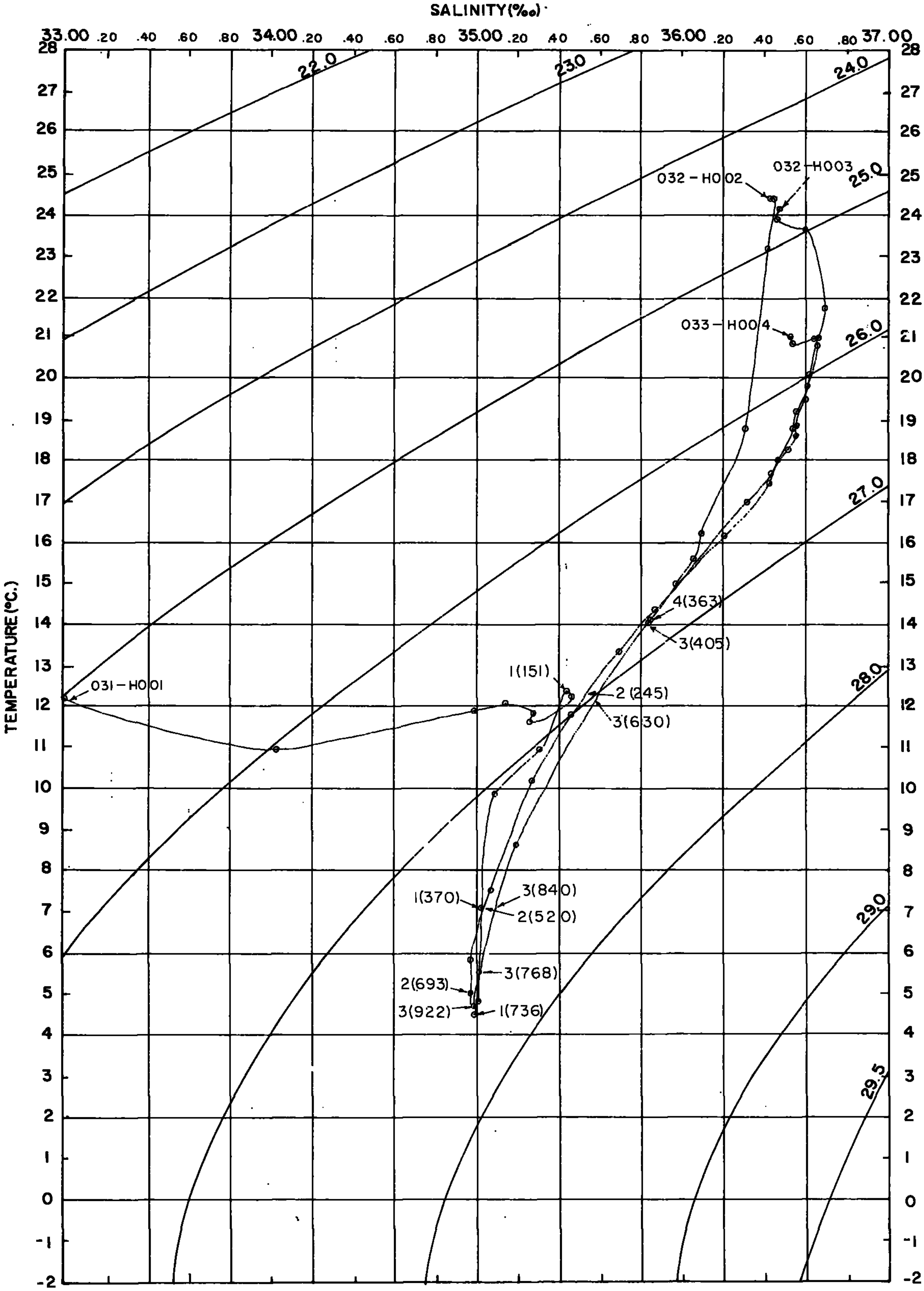

FIGURE 30.—Temperature-salinity curves along section 10. (*See* caption for fig. 27.)

mechanism of mixing during some phase of an interaction cycle, the cross-current component would be produced as a chain effect, and the tendency toward divergence might consequently result in an effective upwelling.

ORIGIN OF THE COLD STRIPES

The cold stripes at the left side of the Gulf Stream are of Shelf water origin, as shown by Ford, Longard, and Banks (1952). Their conclusions were based mainly on two sections (at about long. 55° and 57°) of "Operation Cabot" (1950), which extended over strongly meandering parts of the Gulf Stream. Stommel (1958), generalizing on their results, concluded that the influx of Shelf water must occur somewhere near Cape Hatteras, that the integrity of the cold stripe is maintained for 1,600 miles (2,963 km.), and that water exchange across the boundary is, therefore, negligible.

No such integrity of the cold stripe could be observed during the *Geronimo* cruise. Clear indications that local generation of cold stripes was caused by ascent of cool water may be seen in sections 4 to 7 (figs. 6 to 9). A rather simple boundary structure and no significant cold stripe appear in section 4 (fig. 6). About 12 hours later, when section 6 (fig. 8) was made, the boundary seen in figure 6 was at the same location, but a new boundary and cold stripe were developing strongly 25 miles to the right, far into the Gulf Stream.

The outcropping of cool water seems to have reached a maximum in section 7 (fig. 9). The old boundary is disintegrating below the surface, and the major zone of steeply sloping isotherms is located at the new boundary.

When interaction systems were fully developed and separated from the Gulf Stream by a cold stripe (figs. 10, 14, 16, 17, and 22), the presence of a well-developed mixed layer on both sides of (but not *in*) the stripe, indicated a strong ascending process. Furthermore, the temperatures and salinities of the cold stripes were similar to those in deeper water. For example, the surface temperature in the cold stripe in figure 9 (section 7) is 18° C. No surface salinity values are available for this part of the section, but the previous section (fig. 8) shows a surface salinity of 36.04 ‰ in the newly forming cold stripe (BT 65), while considerably higher surface salinities occur on either side. Salinities and temperatures similar to those found at the surface in the cold stripe in sections 6 and 7 (figs. 8 and 9) were found at a depth of about 160 m. in section 10 at oceanographic station 032–HO02 (fig. 13)—about 20 miles right of the boundary where the isotherms slope steeply. A similar example is provided by the surface conditions at the BT number 269 in figure 17. In figure 22, the surface salinity near the cold stripe (BT 375) is similar to the salinity of the Gulf Stream at 210 m. (station 076–HO40). The hypothesis that the cold stripes were caused by upwelling of water from the area of steeply sloping isotherms seems to be in agreement with the positions of the frontal outcrop as observed from an airplane (Von Arx, Bumpus, and Richardson, 1955). As previously pointed out, a supply of cold, low-salinity water by injection (cold tongues) was also observed during the *Geronimo* cruise. In some portions of the Gulf Stream, this source of cold water to the left of the Gulf Stream may be predominant.

PHOSPHATE DISTRIBUTION

In general, phosphate values were considerably higher in the surface waters of the interaction systems than in the Gulf Stream. Also, phosphate values fluctuated in the interaction systems, associated with interchanging tongues of cold and warm water, and the observed cold-water masses usually showed higher phosphate values. The higher phosphate content of interaction systems could come from various sources, including—although the evidence is sparse— the ascending water. To illustrate this assumption, the only oceanographic station close enough to the cold stripe to be indicative (station 055–HO23 in fig. 17) shows high phosphate values from the surface to about 130 m., low values from about 130 to 300 m., and high values again below 300 m. It seems that at this particular station, ascending water was present above 130 m., and descending mixed water (exhausted of phosphate) between 130 and 300 m. At station 056–HO24 (fig. 17) the phosphate content of the 15° C. water along the steeply sloping isotherms at about 220 m. was about the same. Water in the cold stripe was evidently ascending obliquely at this station, following the sloping density surfaces like Neumann's (1952) "gliding Austausch."

MIXING VOLUMES

According to the described process, Gulf Stream water moves through the interaction system from the surface layer to deeper levels after attaining higher density through mixing. This hypothesis requires mixing of a substantial amount of slope water into the returning mass. Along transect I, the ratio of Gulf Stream water to slope water in the mixture was obtained by applying salinities to the mixing equation, $S(M_1+M_2)=M_1S_1+M_2S_2$ where: M_1 is the mass in the slope water that corresponds to a mean salinity (S_1) of 34.85 ‰. As determined from samples in the upper 150 m., M_2 is the mass of Gulf Stream water corresponding to a mean salinity (S_2) of 36.45 ‰ in the upper 150 m.; S is the resulting salinity of 35.55 ‰, as obtained by computing the mean value of all available T–S curves at the highest points of coinciding properties. The computed proportion of masses was $M_1=1.29\ M_2$, which indicates that a somewhat larger amount of slope water than Gulf Stream was supplied to the mixing process. If all mass separated from the Gulf Stream were to return after mixing, the volume of water returning would be more than double, but such total return seems unlikely.

EFFECT ON ENERGY IN THE GULF STREAM

The departure of part of the dense water to the left side of the Gulf Stream below 300 m. would help to maintain the upper 1,000 m. of the water column at a higher density than would otherwise be the case, and the total mass of dense water would also be increased. In addition, the inflow of dense water at the left side of the Gulf Stream should displace lighter water to the right and consequently increase horizontal pressure gradient across the Stream. Thus, a rotation of mass to the interaction system and back to the Gulf Stream would constitute an energy source contributing to the maintenance, and even intensification, of the Stream. It is hardly possible to assess what proportion of the total complex of individual driving and impeding forces of the Stream such a source of energy would represent; too little is known about that complex. It could be expected, however, that the proportion, although unknown, would be greatest in the late winter and spring, when temperature and density differences between Gulf Stream water and inshore water are large.

SUMMARY

Repeated sections along three transects of the Gulf Stream off Chesapeake Bay in the spring of 1963 revealed a process of interaction between the left flank of the Gulf Stream and the adjacent slope water. The data, though incomplete, suggest the following interpretation of the process:

1. Warm, saline water from the left side of the Gulf Stream was shifted to the left by transient intensified convergence in the slope water–Gulf Stream boundary.
2. This warm water became isolated from the Gulf Stream by divergence near the surface and by upwelling.
3. Intense mixing of the separated Gulf Stream water with the slope water generated a dense water type at depths of about 80 to 180 m.
4. Because of the transient occurrences of unstable mass distribution, a part of the water ($\sigma_t > -27.0$) moved downward and along equal density surfaces and joined with the left side of the Gulf Stream at depths of about 250 to 700 m. Some of the mixed water was probably discharged into secondary streams farther downstream and to the left of the main body of the Gulf Stream.

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